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Technical Report

No. 13301

FINAL REPORT

SERVOJET RETROFIT

CONTRACT NUMBER DAAE07-86-C-R069

JULY 1987

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By _____

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RESEARCH, DEVELOPMENT & ENGINEERING CENTER
Warren, Michigan 48397-5000

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To design and demonstrate a retrofit diesel engine fuel system of an advanced high-pressure concept. By applying the principle of a spill port operated accumulator injector, the system is projected to enhance starting, as well as the idle and part-load operating characteristics of existing engines. The system has been given the model designation SR-1.

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A. CONTRACT NUMBER

DAAE07-86-C-R069

B. PROJECT OBJECTIVE

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C. REPORTING PERIOD

Final Report
August 4, 1986 to June 21, 1987

D. OVERALL PROJECT STATUS

Work has been completed with the evaluation of the retrofit SR-1 injector in DDA 53-series engines. This report documents those results and outlines proposed future programs.

E. TECHNICAL FEASIBILITY

The conventional DDA cam actuated injector can feasibly be modified to take advantage of the Servojet accumulator principal of operation. No significant mechanical problems were encountered during our testing phase either on the bench or during actual engine operation.

It does appear at this time, that a change in air motion characteristics and/or a change in the piston bowl shape will be necessary to take advantage of the higher pressure, and significantly improved fuel atomization.

Engine starting characteristics could not be fully evaluated but were subjectively improved, particularly with the alternate fuels.

F. FUTURE PROGRAM RECOMMENDATIONS

TACOM has expressed an interest in utilizing the fully electronic Servojet system, rather than continuing with the retrofit, mechanically actuated injectors. Further, TACOM has expressed interest in coupling the Servojet system with a proprietary improved turbocharging system. The principal objectives are to improve the low-load performance and maximum power capability. The work is directed towards the Cummins 903 engine rated at a minimum of 600 BHP.

A two-phase program is recommended.

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Phase I

Application of the electronic Servojet fuel injection system to the Cummins 903 engine to improve fuel injection characteristics at low loads and speeds.

The revolutionary system, which has been in development for over 10 years by BKM (U.S. Patent No. 4,628,881), is described in the SAE publication 840273 (Appendix G). Prototypes are being evaluated on five production engines and six single-cylinder engines as a means of reducing gaseous emissions to meet pending legislation.

The accumulator feature of the Servojet fuel system has effectively demonstrated the ability to produce a well atomized spray at all loads and speeds in both bench and operating tests. In addition, the availability of electronically controlled injection timing will provide the opportunity to optimize the injection event for all operating conditions.

A prototype design is available for easy retrofit of the subject engine. Application engineering of the system to the engine will be required to assure the best organization of piping and components.

Phase II

Improved turbocharging system to provide better part-load performance including transient response and to increase power output at the design rating.

The role played by the turbocharger in modern internal combustion engine technology has changed from an optional device to that of an essential part of the engine system. This transition has occurred because of the ability of the turbocharger to control exhaust smoke, engine noise, exhaust emissions and, most important, to achieve high specific power output at reduced fuel consumption. It is also a vital factor in the transient response of the engine to load and speed changes. Finally, the performance of engines at high altitude is enhanced by the ability of the turbocharger to compensate for ambient air density loss. Modern military engines rely heavily on turbocharging to achieve current high-power output levels within the smallest possible weight and package size.

Overall efficiency and performance range of the turbocharger contributes substantially to improving engine performance. BKM, Inc. is proposing new turbocharger technology that utilizes the gains made in commercial turbocharger development and combines these with several new concepts resulting in a highly efficient turbo machine that can achieve the high ratio needed by military engines while retaining the simplicity necessary to guarantee low manufacturing cost. This new design can also incorporate variable geometry components that allow increases in performance range of the engine to which it is applied.

The low inertia which is implicit in the smaller sized unit will have a very beneficial effect on part-load performance and transient response being sought.

The turbocharging improvements will be accomplished on the Cummins 903 engine by substituting twin advanced turbochargers covered by U.S. Patents 4,565,505 and 4,641,977 for the existing single unit. The specific benefits are as follows:

- o The twin arrangement will permit the modification of the exhaust manifolds to provide separate branches, each exhausting two cylinders into the divided turbine housing. This improved utilization of pulse energy not only improves low load and speed operation but also the transient characteristics.
- o Conservation of exhaust energy due to shorter, more direct exhaust entry to the turbo.
- o Reduced rotor inertia afforded by the unique design for quicker acceleration and reduced smoke.
- o Low-friction bearing design for improved BSFC and acceleration.
- o Increased power output with up to 700 hp regarded as a realistic objective.
- o Further horsepower expansion practical with addition of variable geometry and axial stage in the compressor section.
- o Potential of a future simplified two-step exhaust redirection system for further low-load improvement.

G. PROJECT SUMMARY

The Servojet injection nozzle, employing an accumulator for injection energy storage, can be actuated by mechanical means, achieving most of the very desirable effects without the use of electronic controls. This system was designed for easy retrofitting to current engines for improving combustion, part-load fuel economy, and starting characteristics. The system was expected to be particularly effective at load speeds and be more tolerant of low cetane fuels.

The Servojet retrofit injection nozzle, SR-1, was designed, built and tested to evaluate comparative performance characteristics with the conventional mechanical unit injector. Tests conducted at BKM, the University of Wisconsin, and Michigan Technical University verify the improved performance characteristics at low and medium speeds (750 and 1600 RPM). The performance advantages were improved starting; ability to operate satisfactorily with very low cetane fuels; fast and efficient combustion; lowered NOx emissions; and reduced fuel consumption.

At operating speeds above 1600 RPM, the performance with the Servojet system deteriorated as compared to the standard fuel injection system. Since the fuel spray characteristics are independent of speed, the falloff in performance was attributed to a mismatch between the fuel spray characteristics and the air motion or combustion chamber shape. Further development work, beyond the scope of this program, is being undertaken to resolve the problems of matching injection spray characteristics with air motion in the combustion chamber.

The testing discussed in this final report includes results from engine testing and combustion flame photographs.

The Servojet injection principal is proprietary and patented (U.S. Patent No. 4,628,881) with plans well underway for the commercial introduction of both the mechanical and full authority electronically controlled systems.

H. TEST WORK DISCUSSION

1. DDA 53 Series Engine Testing

This testing was conducted at the University of Wisconsin (Madison) with the cooperation of Prof. Gary Borman. A single-cylinder DDA 53-series engine was utilized. The engine was equipped with a cylinder pressure transducer for providing data to a PEI combustion analyzer, having a 0.2 degree crankshaft angle resolution.

Additional instrumentation for monitoring smoke, nitrides of oxygen, fuel consumption and torque was utilized.

Tests results showed, at 1200 RPM, the Servojet injectors exhibited lower fuel consumption and NOx levels than with the engine equipped with standard N 65 conventional injectors. As indicated on the developed data, the mass burning rate of the fuel is approximately three (3) times faster than the standard without an increase in cylinder peak pressure.

On the negative side, rates of pressure rise increased from approximately 150 to 300 psi/degree. Smoke was also higher, especially at light loads and higher speeds. This was contrary to what was expected in light of the poor spray characteristics of the standard injector at low speeds and light loads.

Fuel consumption also degraded from standard as the engine speed increased.

Two nozzle tips were evaluated on the SR-1 injector, an 8-hole x 0.26 diameter and a 12-hole x 0.23. In all cases up to and including 2000 RPM, the 12-hole nozzle tip exhibited the lowest oxides of nitrogen but the highest smoke.

It was not within the scope of this project to develop either the spray characteristics or combustion conditions for providing a compatible combination which would result in across the board improvements. However, we can make several hypotheses as to the cause of the differences.

a. Increased Fuel Consumption at Increased Speeds

The fuel atomization resulting from the Servojet injector is significantly improved over that resulting with the standard injector. Because of the trend of deterioration with increased speed, we believe it is related to the increase in air swirl coupled with the reduced penetration of the SR-1 spray. This results in a rich cloud of fuel near the center of the combustion chamber, which does not burn efficiently and continues to burn late into the expansion stroke. Additionally, slightly more parasitic loss may result with the SR-1 injector due to the 30% increase of peak injection pressure.

Graphs included in Appendix A illustrate the fuel rate as compared with BMEP (Willans lines) showing both that achieved with the stock system and the Servojet with two different tips. The NOx results are also included in Appendix A.

b. Increased Smoke Levels at Increasing Speeds

The increased smoke level may result from the same basic argument made about the cause of increased fuel consumption. Smoke also increased as a function of engine speed. Appendix B contains graphs illustrating the trends described.

Since the fuel spray characteristics of the Servojet system are independent of engine speed, the degrading of both fuel consumption and smoke levels was attributed to a mismatch between the fuel spray characteristics and the air motion and/or combustion chamber shape. From combustion flame photographs, it was evident that the rotational motion of the combustion chamber gases is about 10 times the rotational speed of the crankshaft. From this observation, it was concluded that the high swirl velocities deflect the highly atomized fuel plume and prevent adequate penetration for mixing with air at the outer periphery of the combustion chamber. Flame photos for both standard and Servojet equipped engines are included as Appendix C.

Further development work, beyond the scope of this program, is being undertaken for determining the different parameters which will result in proper matching of all elements.

c. High Rate of Pressure Rise

Cylinder pressure, rate of heat release and mass burn rate were recorded and plotted by the combustion analyzer, and included as Appendix D. For the stock unit injector, the rate of combustion in real time shows a marked increase since the time to burn 95% of the mass is essentially constant in degrees, yet speed is 60% higher. Consequently, the absolute rate of heat release increases approximately 50%.

On the other hand, for the Servojet system, the time to burn 95% has increased about 4 times, with the same speed increase of 60%. This represents a 40% decrease in the absolute rate of combustion.

Such an effect can only be attributed to a very marked change in the fuel/air mixing process.

It was further noted that the same effect was exhibited at both part and full loads.

It was therefore hypothesized that the highly atomized spray resulting with the Servojet system requires a change in air motion and/or combustion chamber shape in order to realize the full advantages associated with the improved spray atomization characteristics.

A summary of the mass burned and rate of heat release at 1200 RPM are included as Figures 1 and 2. Figure 3 compares the mass burned of the standard injector, Servojet with a 8H26 tip and Servojet with a 12H tip.

Figure 1 also contains selected data comparing ISFC, NOx and smoke levels for three different set-ups.

Figure 4 illustrated the relative mass burning rate of the three injector set-ups.

A complete set of test data is included in Appendix D.

2. OPTICAL COMBUSTION ANALYSIS

An optical combustion analysis using high-speed photography (10,000 frames per second) was utilized to study the combustion resulting from the Servojet concept, comparing it to the stock. Additionally, alternate fuels, spark-ignited, were investigated.

This work was conducted by Michigan Technical University in Houghton, Michigan under the direction of Dr. Duane Abata.

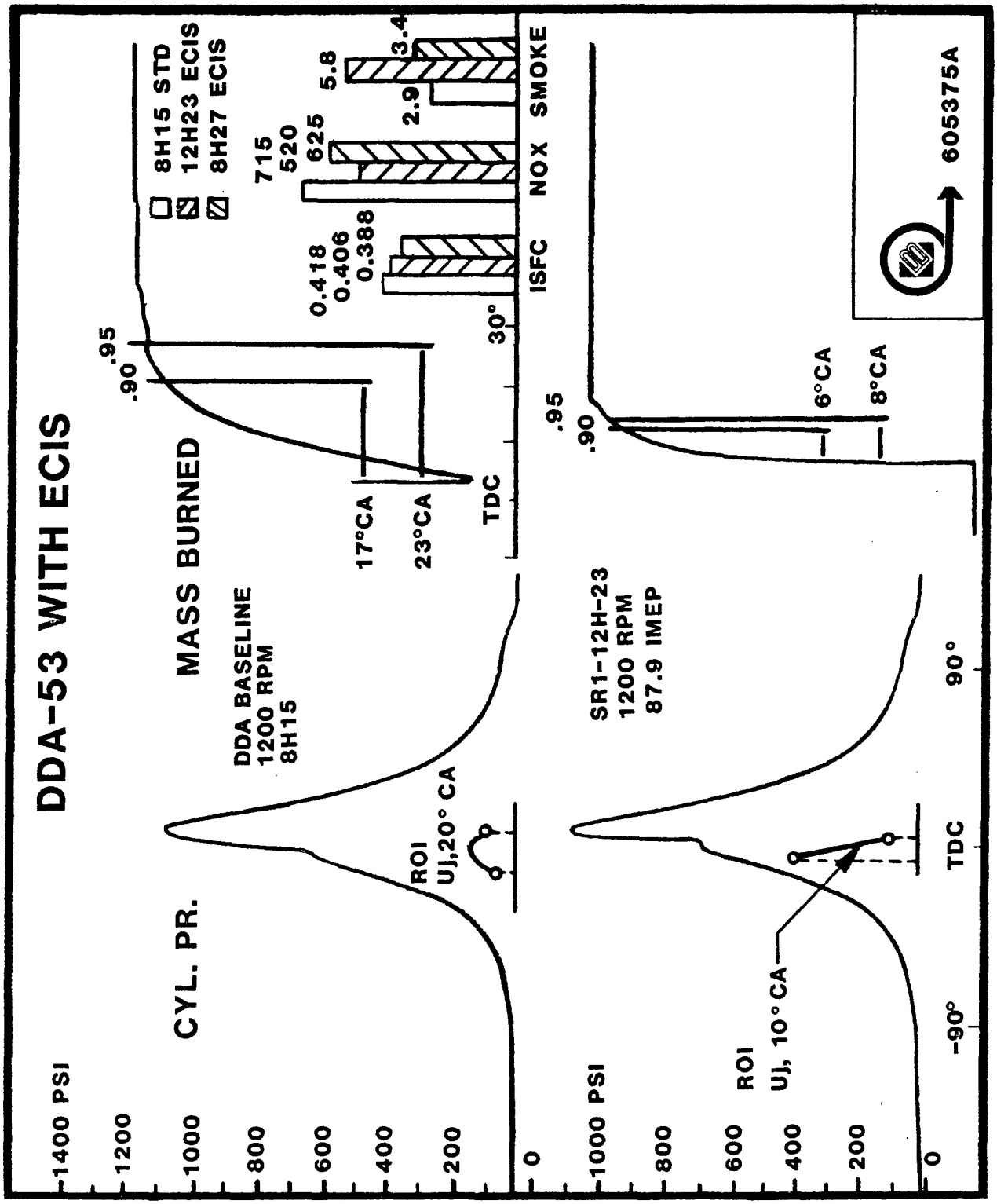
DDA-53 WITH ECIS
CYL. PR.
1400 PSI
1200
1000
800
600
400
200
0
ROI
UJ,20° CA
DDA BASELINE
1200 RPM
8H15
MASS BURNED
.95
.90
17°CA
23°CA
TDC
30°
8H15 STD
12H23 ECIS
8H27 ECIS
0.418
0.406
0.388
715
520
625
2.9
5.8
3.4
ISFC NOX SMOKE
SR1-12H-23
1200 RPM
87.9 IMEP
6°CA
8°CA
605375A
1000 PSI
ROI
UJ, 10° CA
-90°
TDC
90°

Figure 1

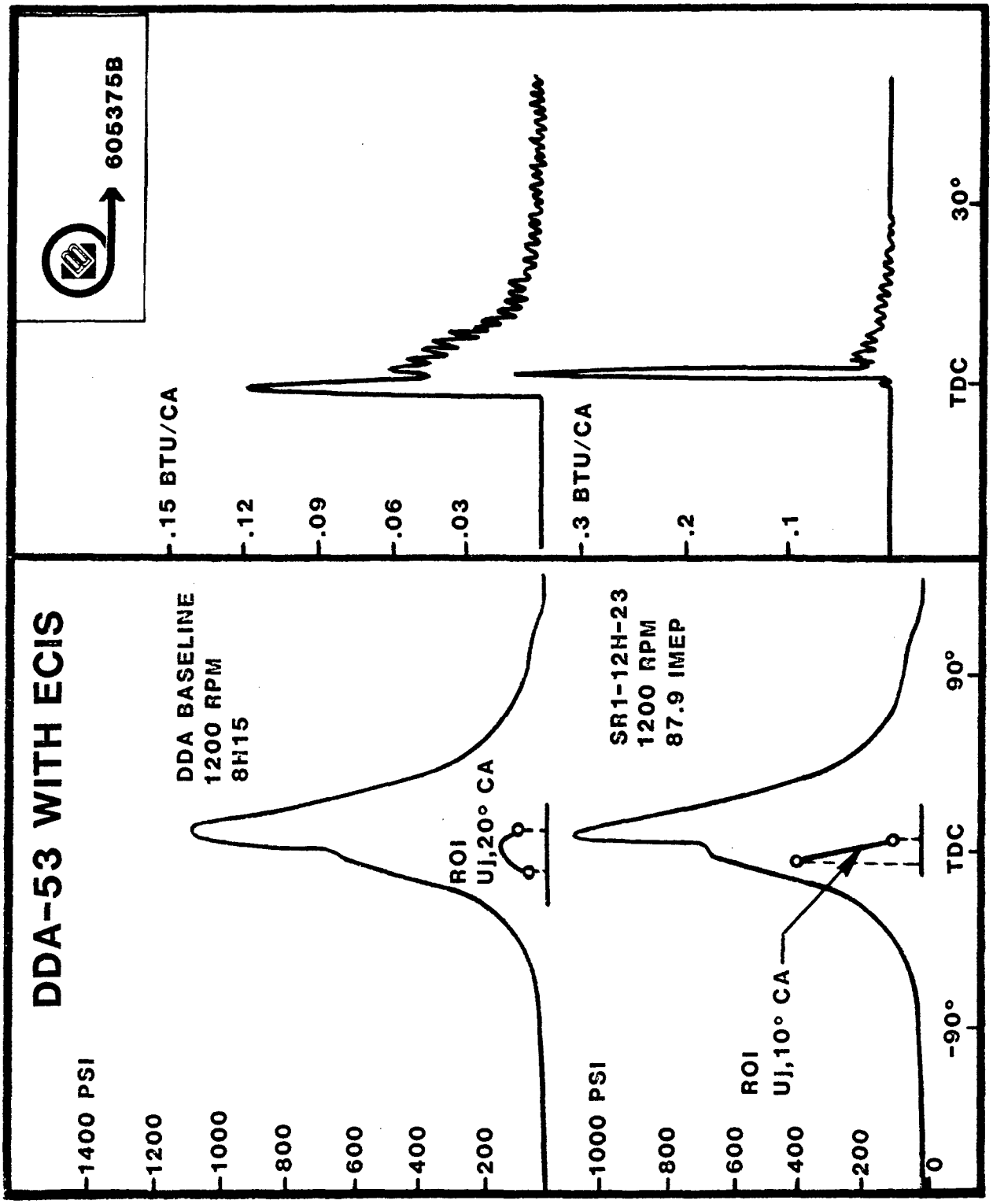
DDA-53 WITH ECIS
6065375B
DDA BASELINE
1200 RPM
8H15
SR1-12H-23
1200 RPM
87.9 IMEP
ROI
UJ,20° CA
ROI
UJ,10° CA
1400 PSI
1200
1000
800
600
400
200
1000 PSI
800
600
400
200
0
.15 BTU/CA
.12
.09
.06
.03
.3 BTU/CA
.2
.1
-90°
TDC
90°
TDC
30°

Figure 2

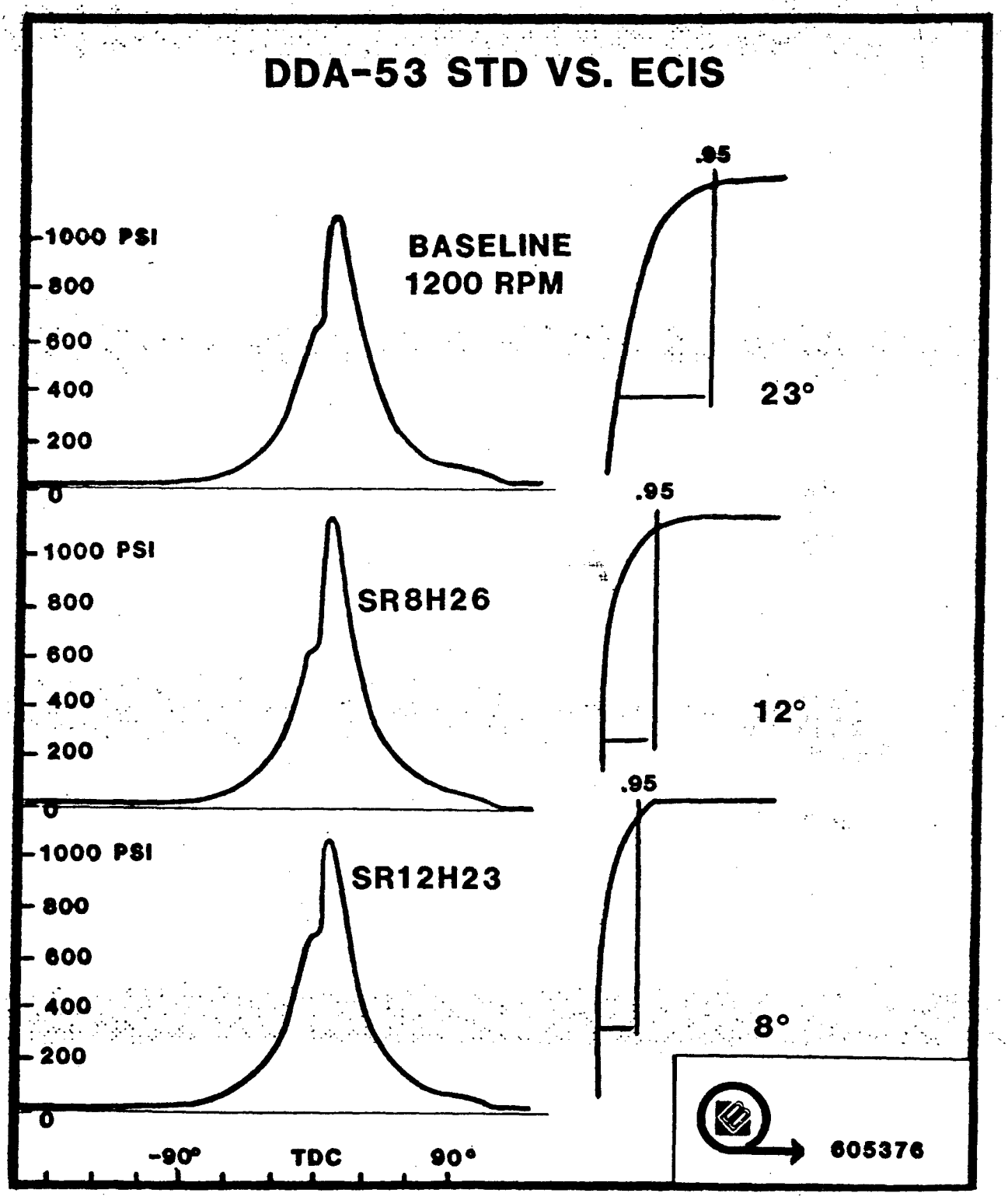
DDA-53 STD VS. ECIS
1000 PSI
800
600
400
200
0
BASELINE
1200 RPM
.95
23°
SR8H26
12°
SR12H23
8°
-90°
TDC
90°
605376

Figure 3

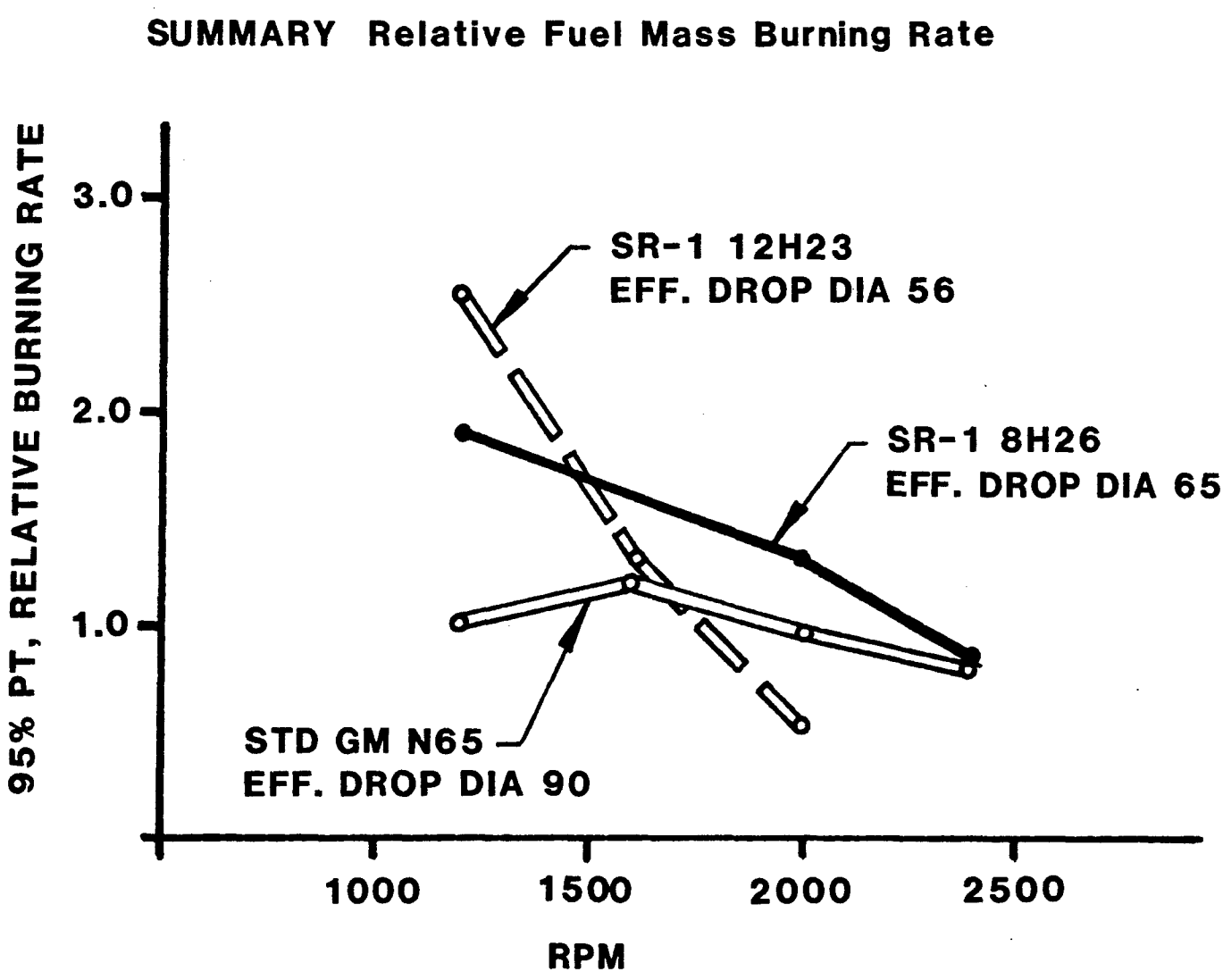
SUMMARY Relative Fuel Mass Burning Rate
95% PT, RELATIVE BURNING RATE
3.0
2.0
1.0
SR-1 12H23
EFF. DROP DIA 56
SR-1 8H26
EFF. DROP DIA 65
STD GM N65
EFF. DROP DIA 90
1000
1500
2000
2500
RPM
605378

Figure 4

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The engine used was a modified single-cylinder DDA 53-series. The engine had a flat port window installed into the top of the piston with the cylinder head surface of the block raised to facilitate the installation of an extra long piston. This provides a viewing slot for a mirror used to project the combustion picture 90 degrees from the cylinder axis.

Because of these modifications, engine operation was limited to below 1000 RPM and 75% of the maximum load that can be applied to a nonmodified engine. At these conditions, the mechanically actuated stock injector is handicapped by low injection pressure and long injection duration, approximately 15% crank. The Servojet injector, operates at approximately full injection pressure (20,000 psi) with a very short duration of about 3 crankshaft degrees. A summary of the combustion photographs contained in Appendix D is included as Figure 5.

Data from these tests together with Dr. Abata's progress report number 11 to Dr. Sung Lee of the Keweenan Research center are also included in Appendix D.

With the Servojet injector, the rate of heat release was found to be very rapid. However, the penetration of the fuel into the chamber was shorter than with the stock injector due to the greatly improved atomization.

Type I and II fuels were also evaluated using a spark to assist ignition.

Combustion was found to be most improved over that achieved with the stock injector. Combustion knock was significantly reduced as well.

With the Type II fuel and the Servojet injector, combustion was initiated by autoignition and was found to be independent of the spark. With the standard injector, many cycles with the spark were required to achieve ignition and smooth combustion. The Servojet injector presented fuel which resulted in almost instantaneous ignition upon the initial injection of fuel into the combustion chamber.

It should be noted that the resulting combustion bowl in the modified piston was of a flat bottom bowl, or "hockey puck" shape. This shape may prove to be more favorable to the Servojet injection characteristics, resulting in a more uniform fuel/air mixture through the chamber.

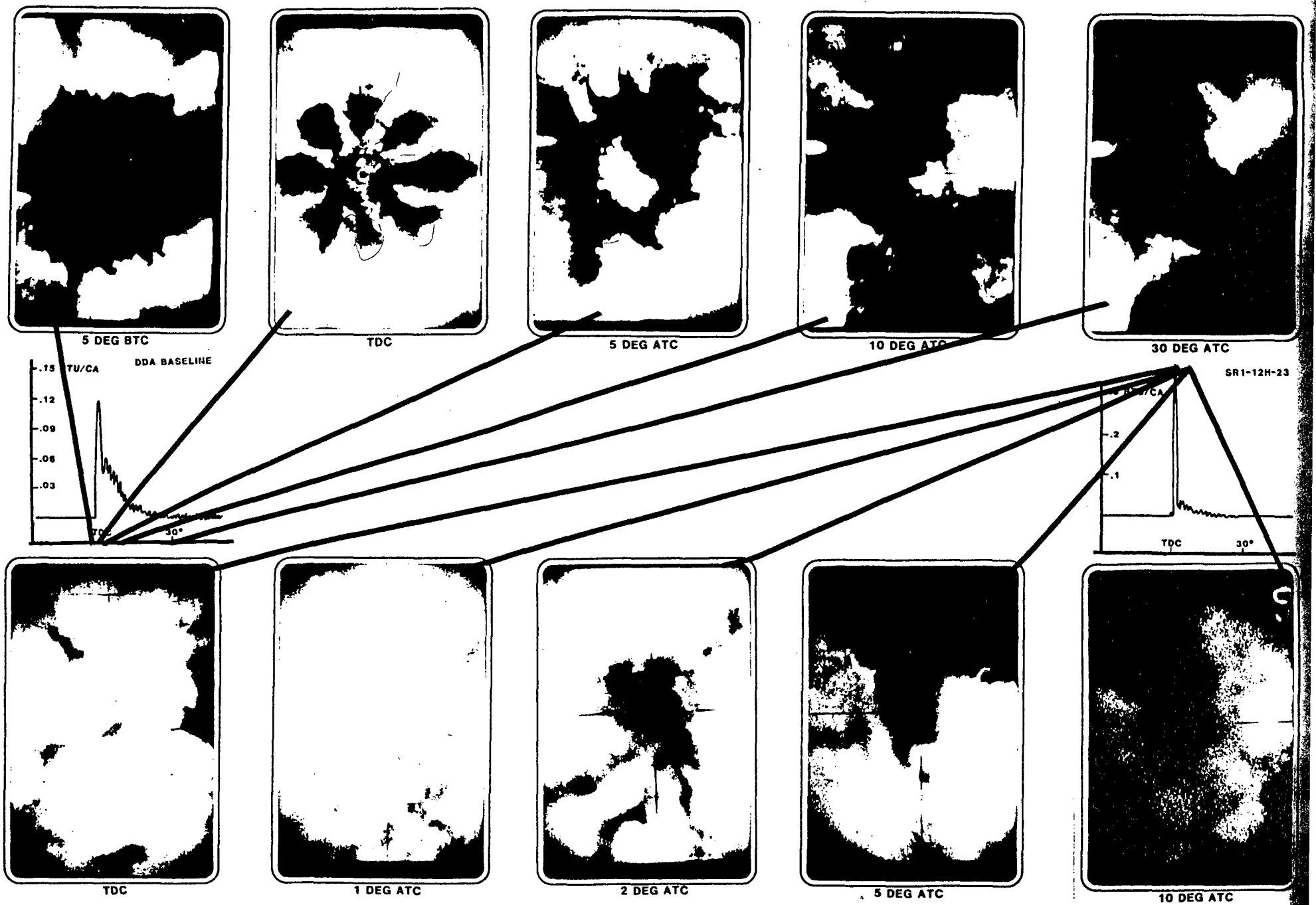

5 DEG BTC
TDC
5 DEG ATC
10 DEG ATC
30 DEG ATC
DDA BASELINE
.15 TU/CA
.12
.09
.06
.03
TDC
30°
SR1-12H-23
.2
.1
TDC
30°
TDC
1 DEG ATC
2 DEG ATC
5 DEG ATC
10 DEG ATC

Figure 5

The following comparative chart can be concluded from the test work:

Performance Characteristics	Stock Injector	Servojet Injector
Start of Ignition	Slow and Scattered, 8 degrees BTC	Instant, uniformly distributed, @ TDC
Ignition Delay	10 degrees ca	5 degrees ca
Ignition of low cetane fuel	Poor	Excellent
Wall Impingement	Heavy	None
Distribution of combustion fuel/air mixture	Concentrated at outer periphery of chamber	Uniform
Burn time	48 degrees ca	10 degrees ca

I. FINANCIAL STATEMENT

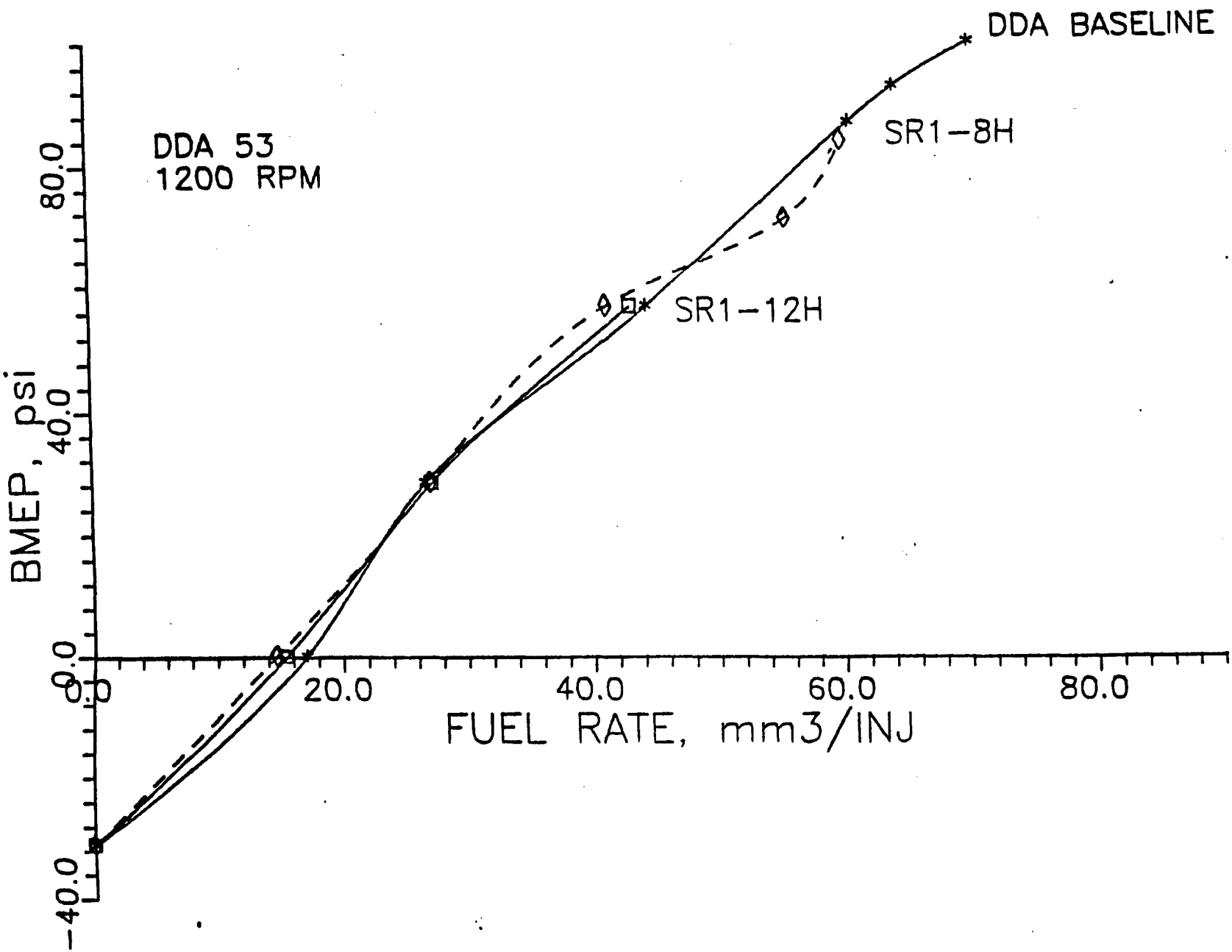
See Appendix E

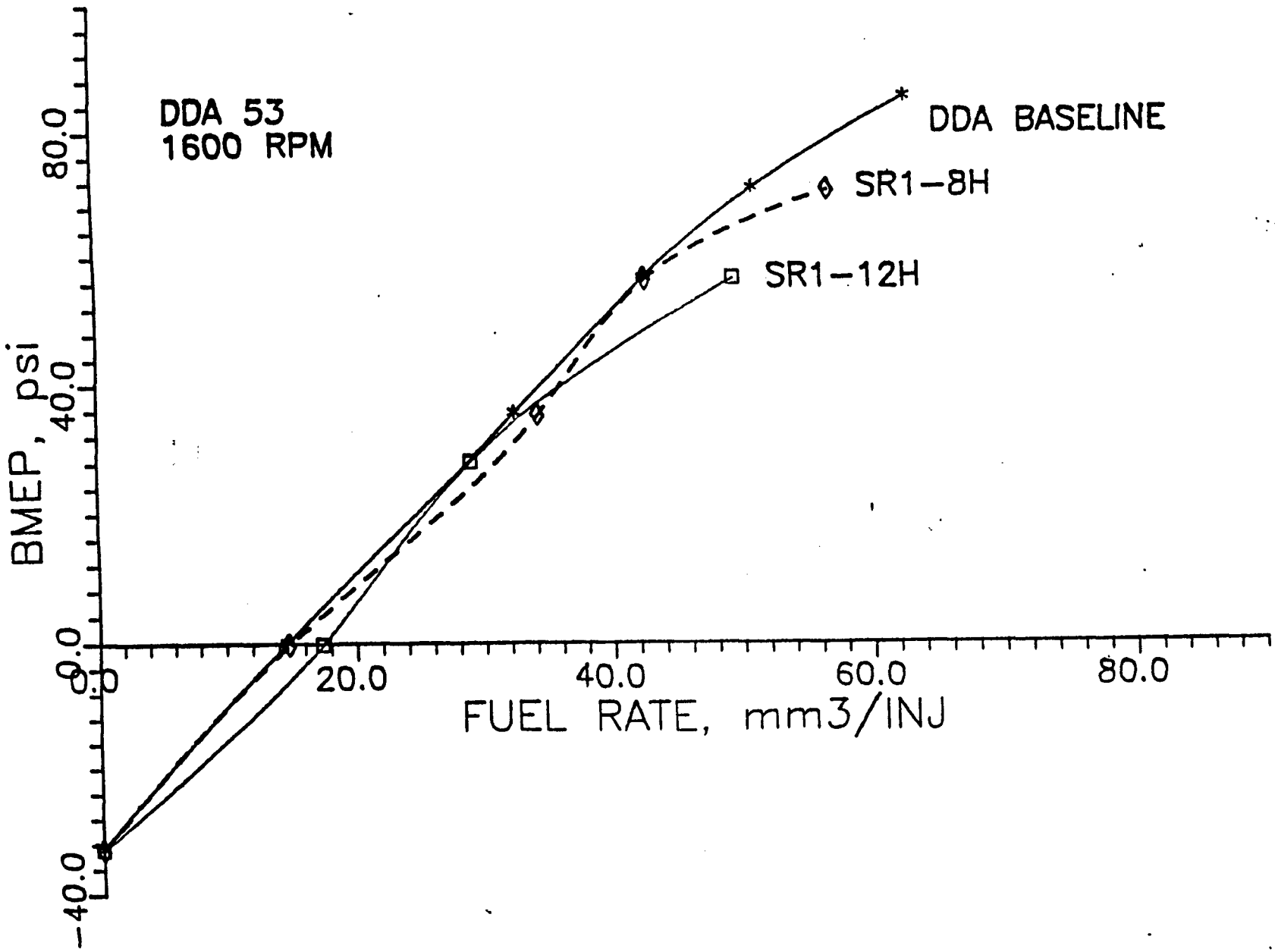
J. EXPENDITURE HISTORY

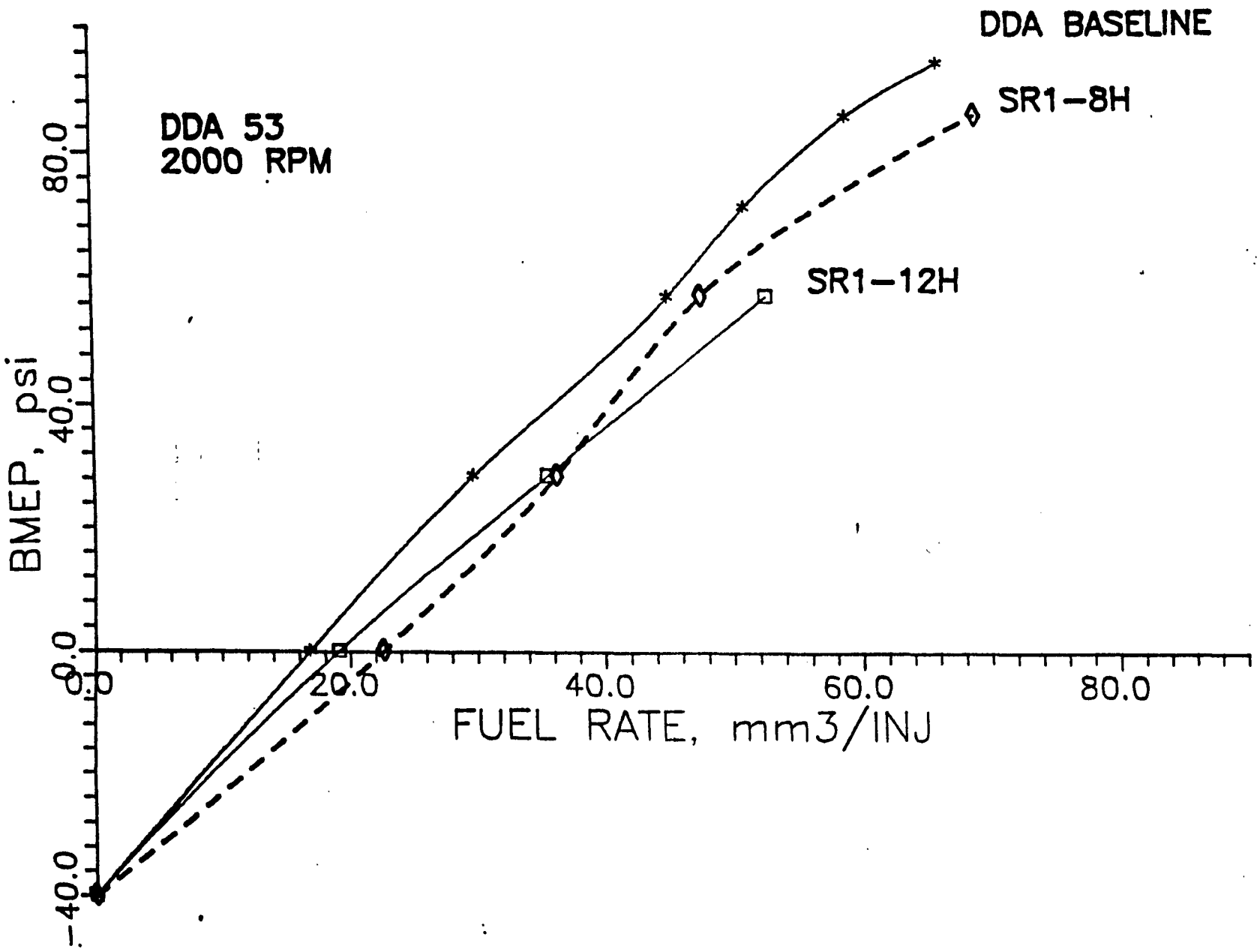
See Appendix F

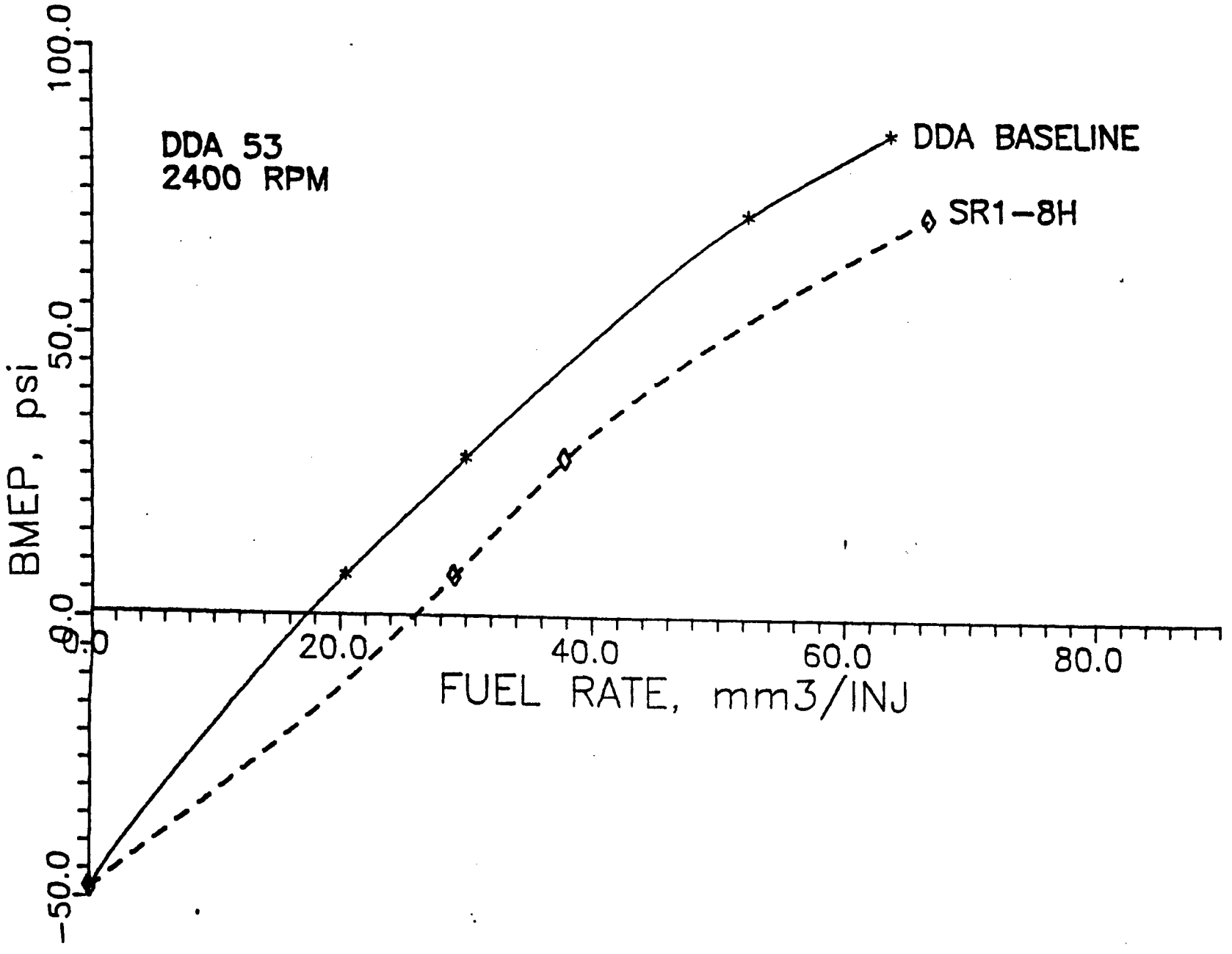
APPENDIX A

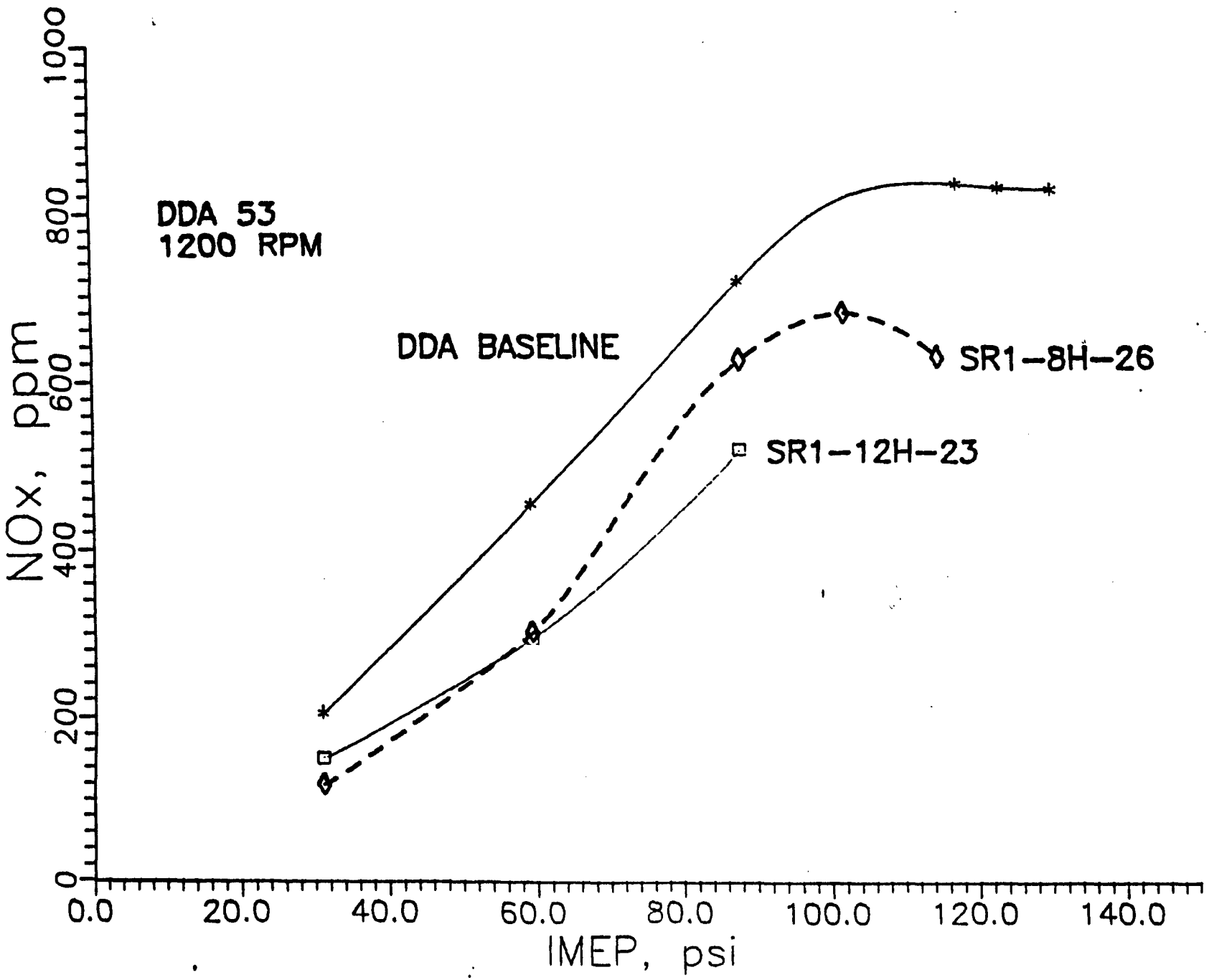
FUEL RATE AND NOx GRAPHS

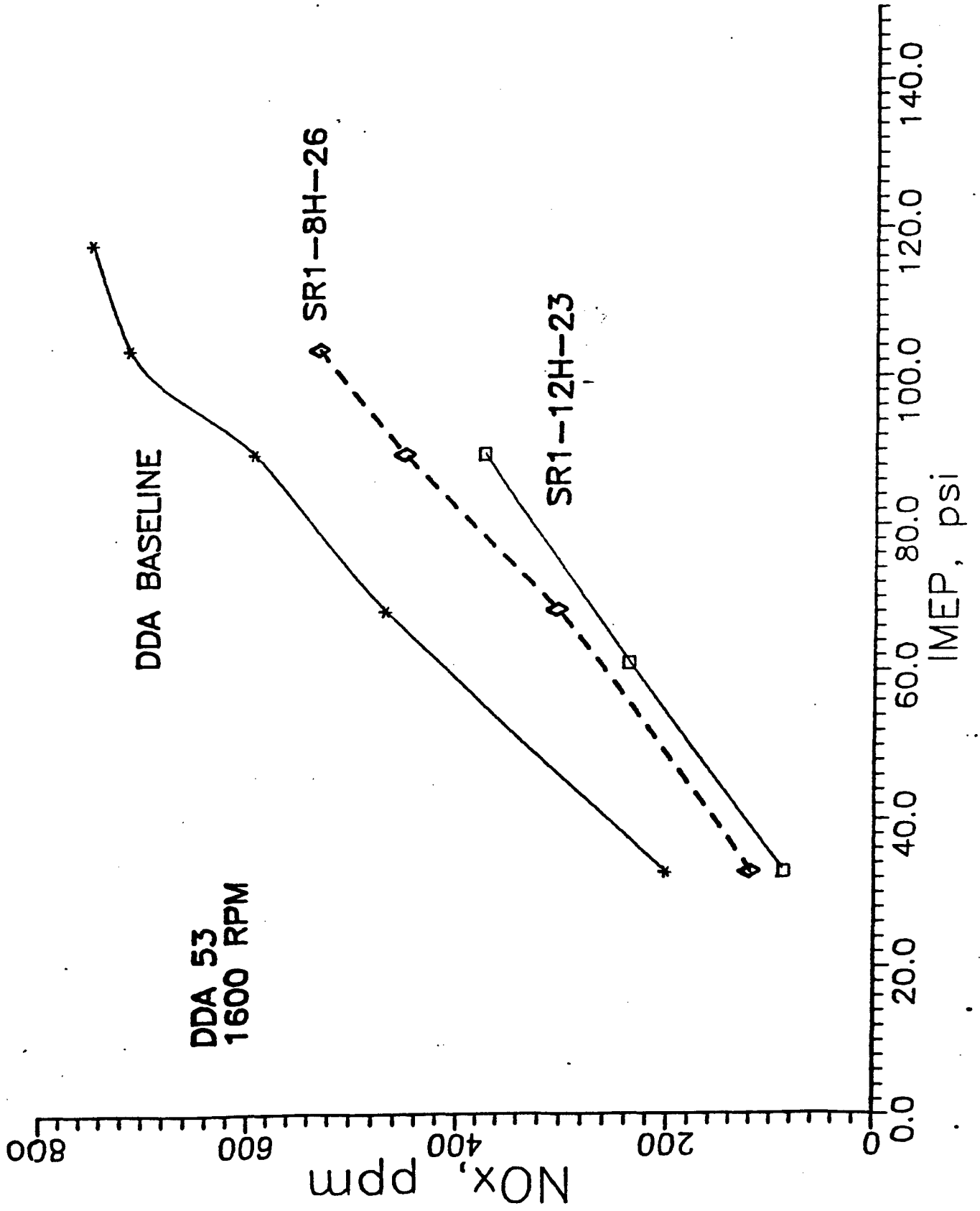

DDA BASELINE
SR1-8H
SR1-12H
DDA 53
1200 RPM
BMEP, psi
80.0
40.0
0.0
-40.0
0.0
20.0
40.0
60.0
80.0
FUEL RATE, mm3/INJ

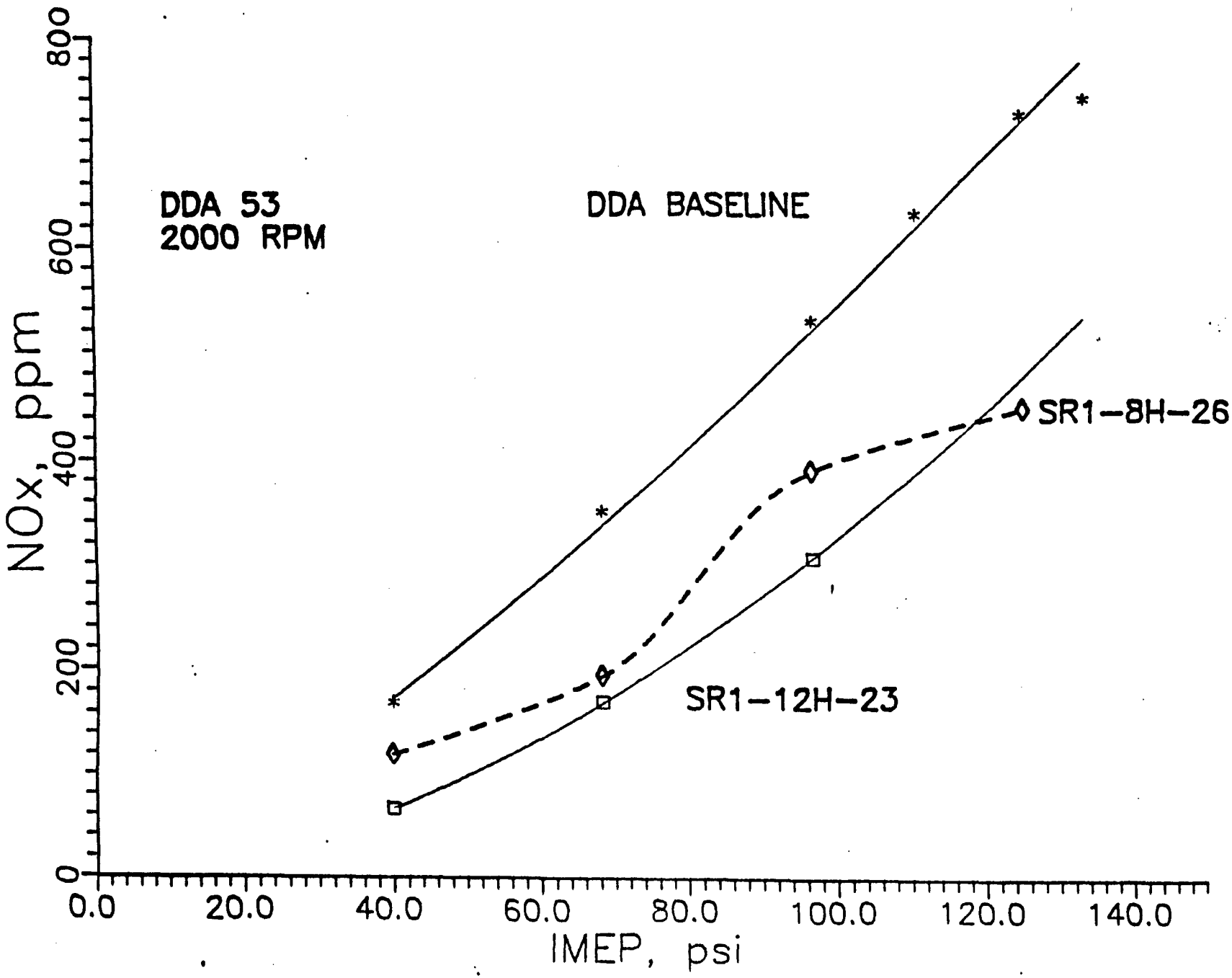

DDA 53
1600 RPM
DDA BASELINE
SR1-8H
SR1-12H
BMEP, psi
80.0
40.0
0.0
-40.0
0.0
20.0
40.0
60.0
80.0
FUEL RATE, mm3/INJ


DDA BASELINE
SR1-8H
SR1-12H
DDA 53
2000 RPM
BMEP, psi
80.0
40.0
0.0
-40.0
0.0
20.0
40.0
60.0
80.0
FUEL RATE, mm3/INJ


DDA 53
2400 RPM
DDA BASELINE
SR1-8H
BMEP, psi
100.0
50.0
0.0
-50.0
0.0
20.0
40.0
60.0
80.0
FUEL RATE, mm3/INJ


DDA 53
1200 RPM
DDA BASELINE
SR1-8H-26
SR1-12H-23
NOx, ppm
0
200
400
600
800
1000
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
IMEP, psi


DDA 53
1600 RPM
DDA BASELINE
SR1-8H-26
SR1-12H-23
NOx, ppm
0
200
400
600
800
IMEP, psi
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0


DDA 53
2000 RPM
DDA BASELINE
SR1–8H–26
SR1–12H–23
NOx, ppm
0
200
400
600
800
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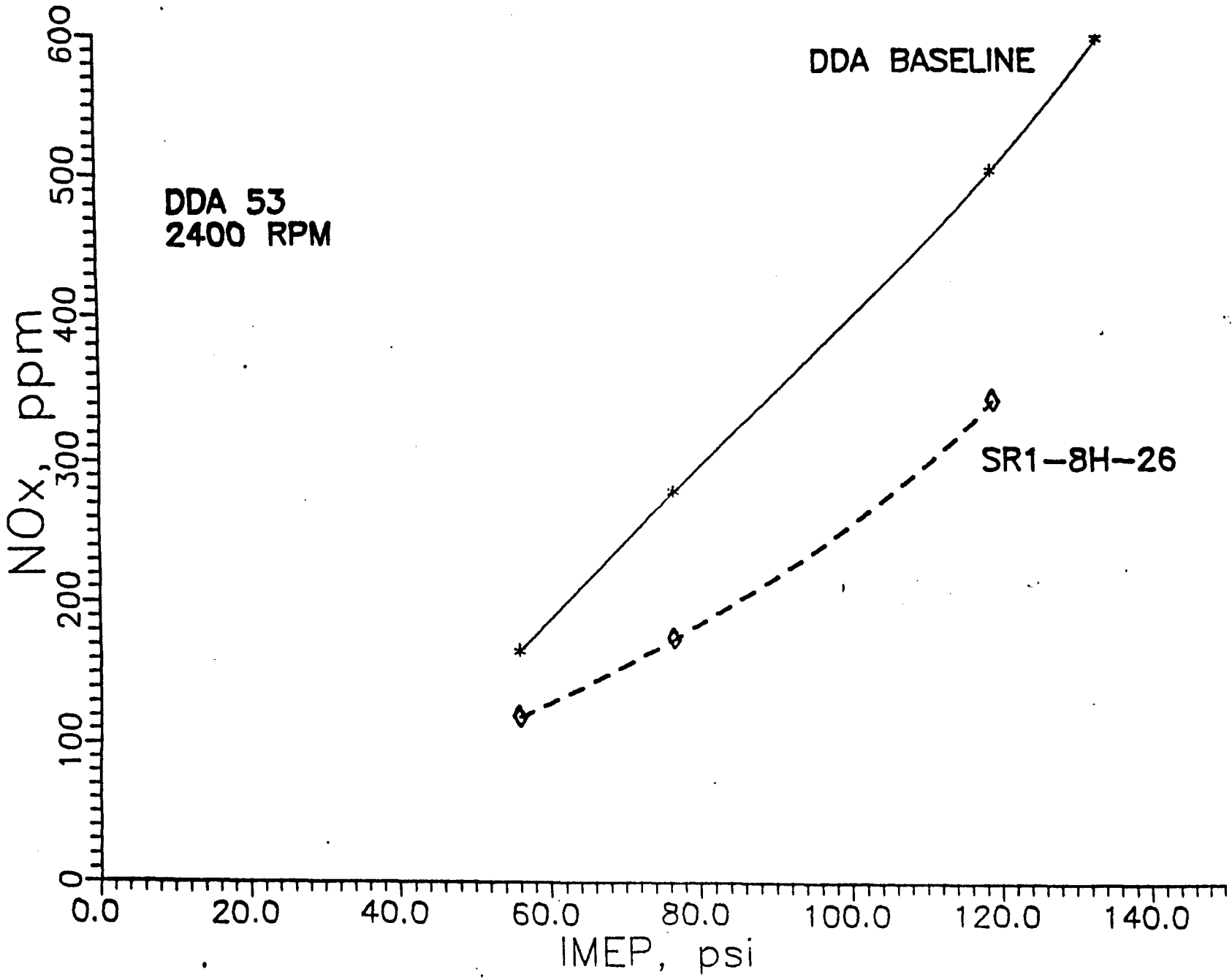
40.0
60.0
80.0
100.0
120.0
140.0
IMEP, psi


DDA 53
2400 RPM
DDA BASELINE
SR1-8H-26
NOx, ppm
0
100
200
300
400
500
600
0.0
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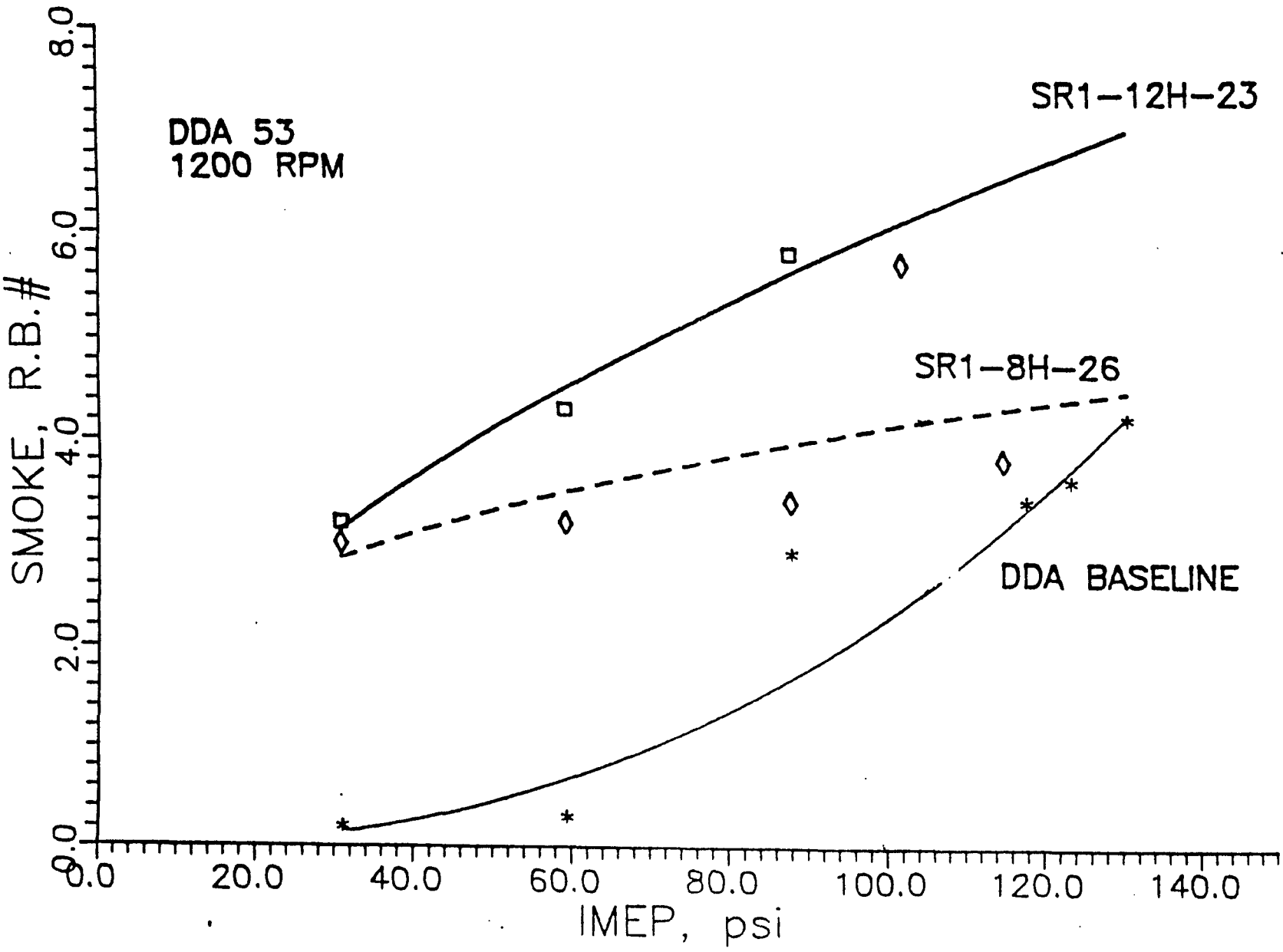
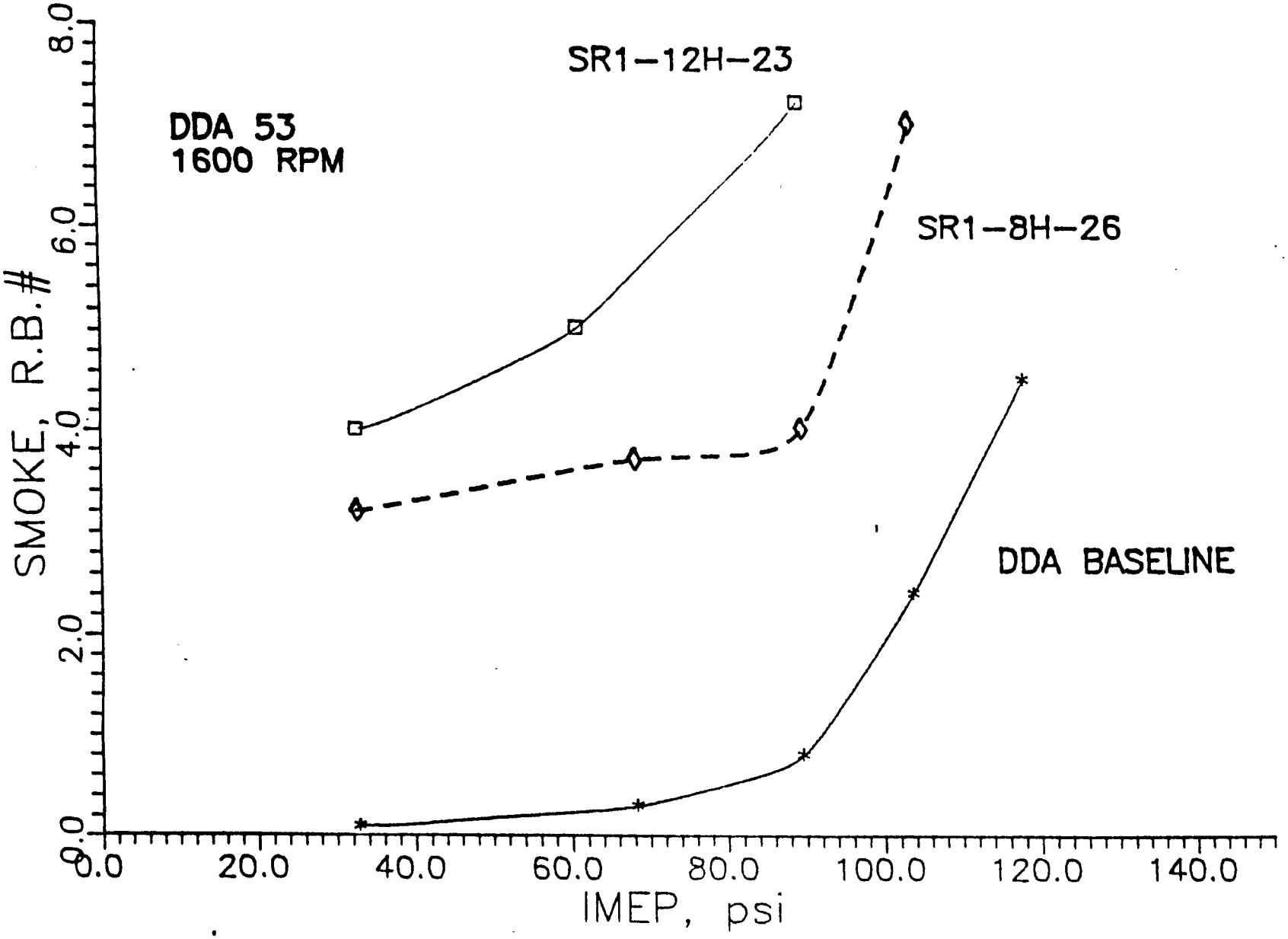
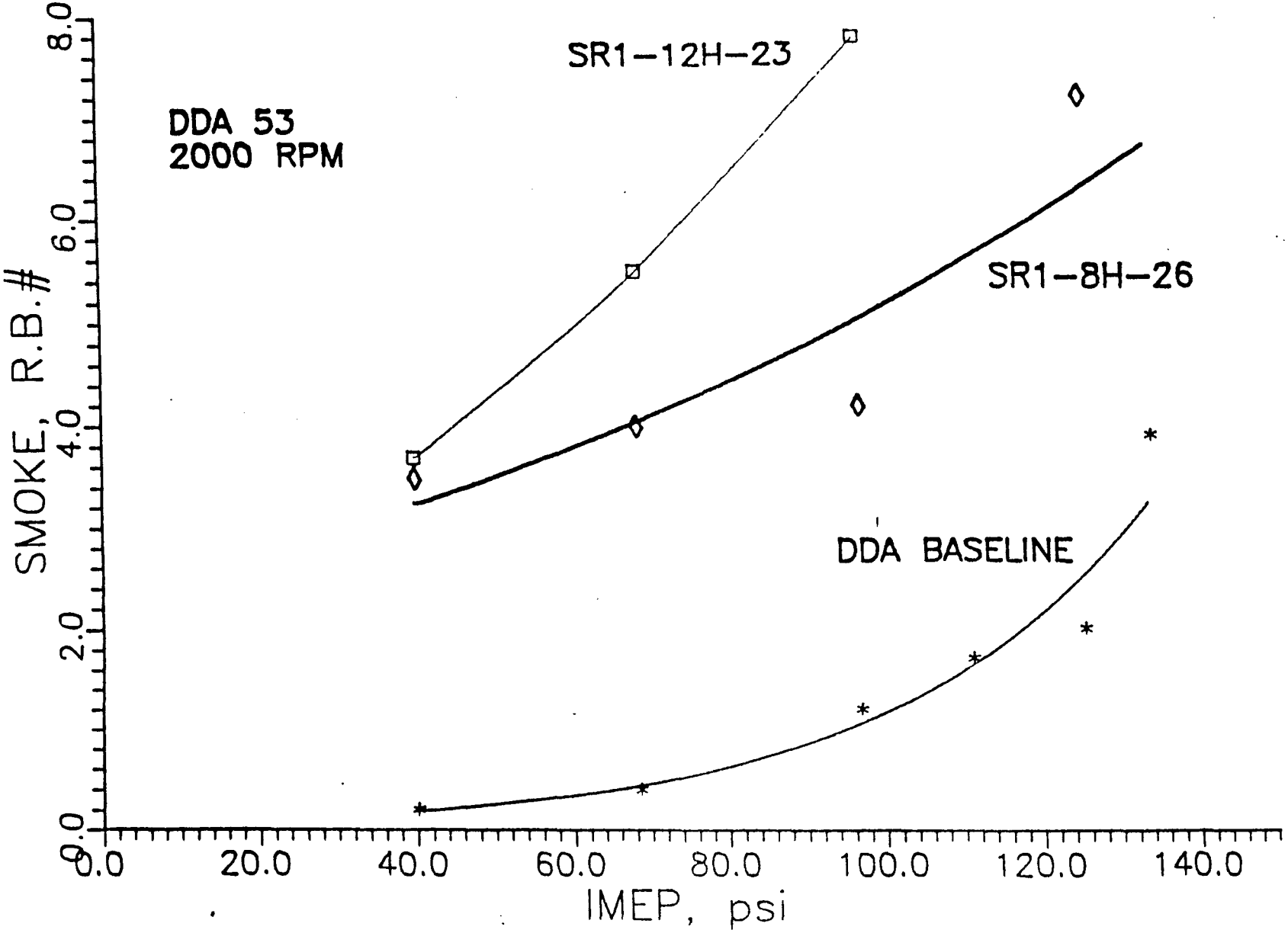
40.0
60.0
80.0
100.0
120.0
140.0
IMEP, psi

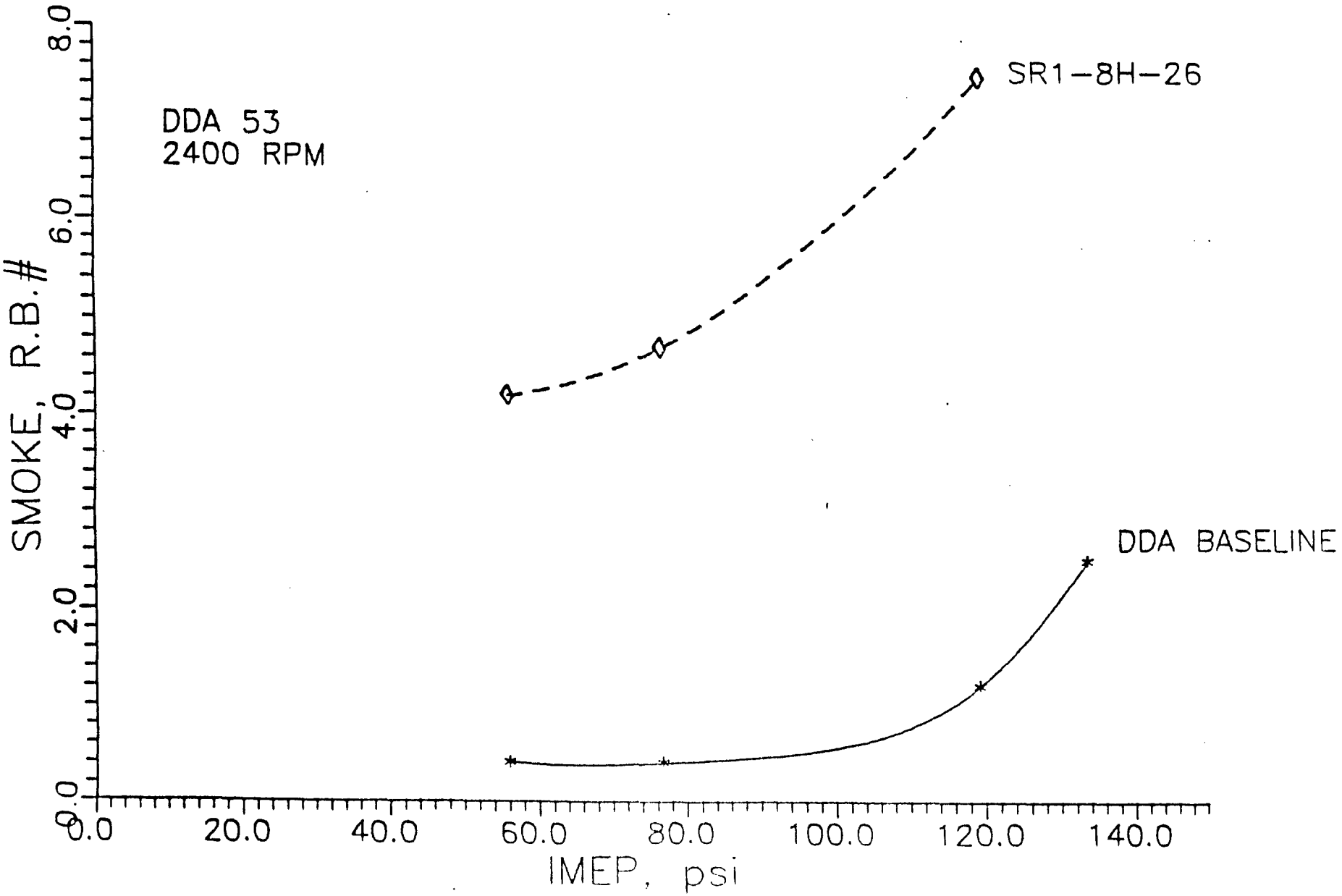
APPENDIX B

SMOKE DATA


DDA 53
1200 RPM
SR1–12H–23
SR1–8H–26
DDA BASELINE
SMOKE, R.B.#
IMEP, psi
0.0
2.0
4.0
6.0
8.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0


SR1-12H-23
DDA 53
1600 RPM
SR1-8H-26
DDA BASELINE
SMOKE, R.B.#
0.0
2.0
4.0
6.0
8.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
IMEP, psi

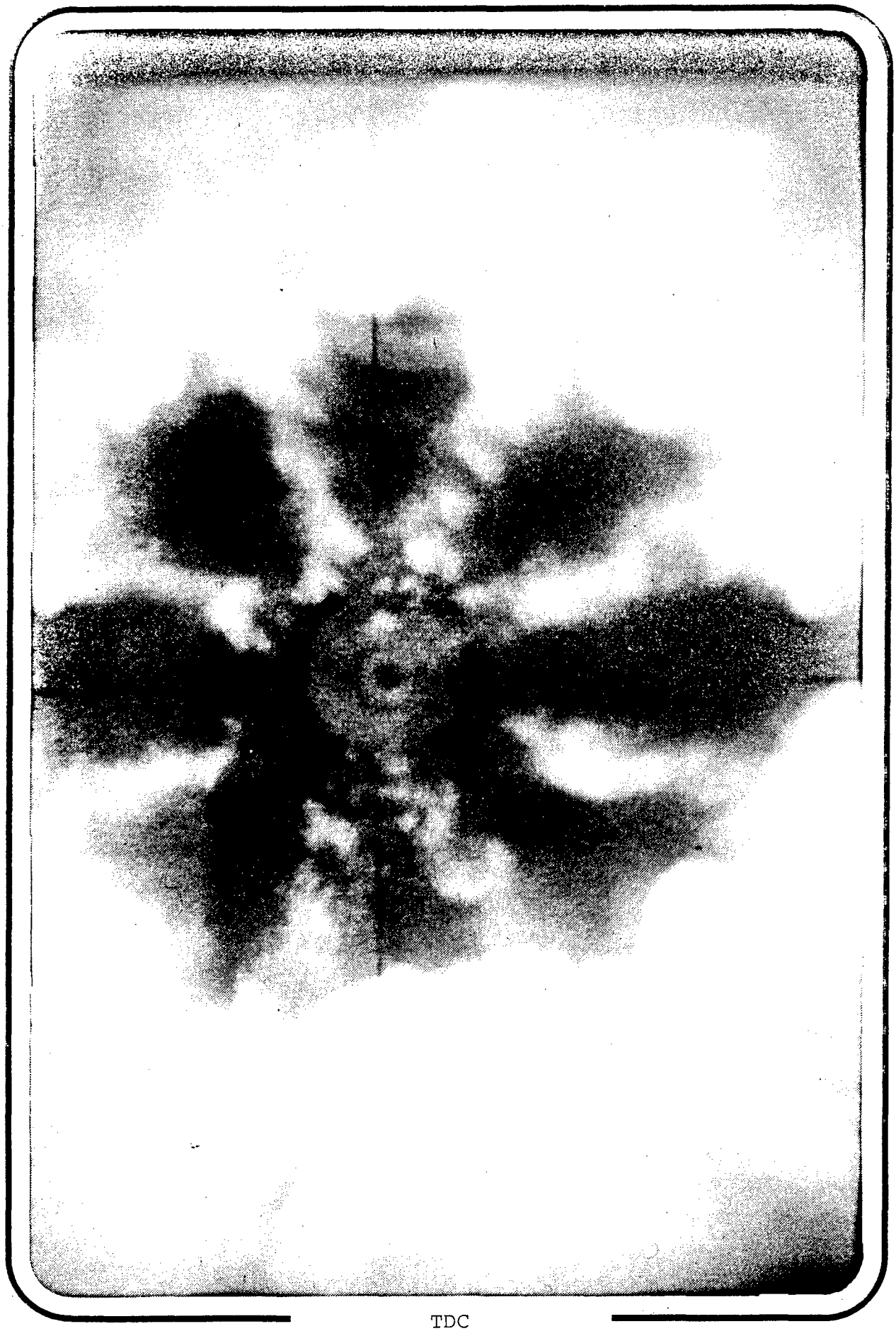

DDA 53
2000 RPM
SR1–12H–23
SR1–8H–26
DDA BASELINE
SMOKE, R.B.#
IMEP, psi
0.0
2.0
4.0
6.0
8.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0


DDA 53
2400 RPM
SR1-8H-26
DDA BASELINE
SMOKE, R.B.#
0.0
2.0
4.0
6.0
8.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
IMEP, psi

APPENDIX C

FLAME PHOTOGRAPHS AND DATA

5 Deg. BTC
DDA BASELINE
8H15 C-2



TDC
DDA BASELINE
8H15
C-3

5 Deg. ATC
DDA BASELINE
8H15

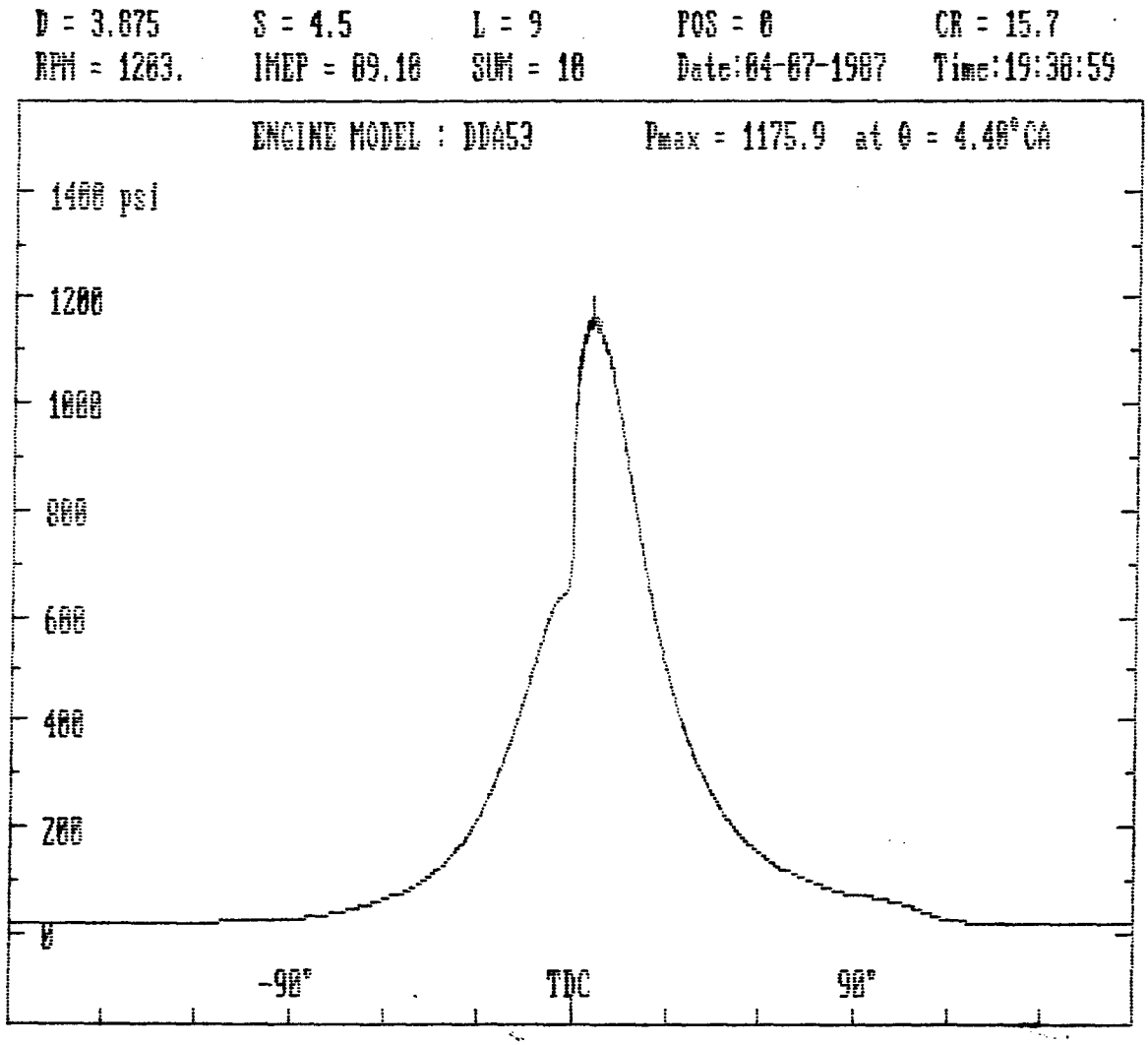
10 Deg. ATC
DDA BASELINE
8H15
C-5

30 Deg. ATC
DDA BASELINE
8H15 C-6

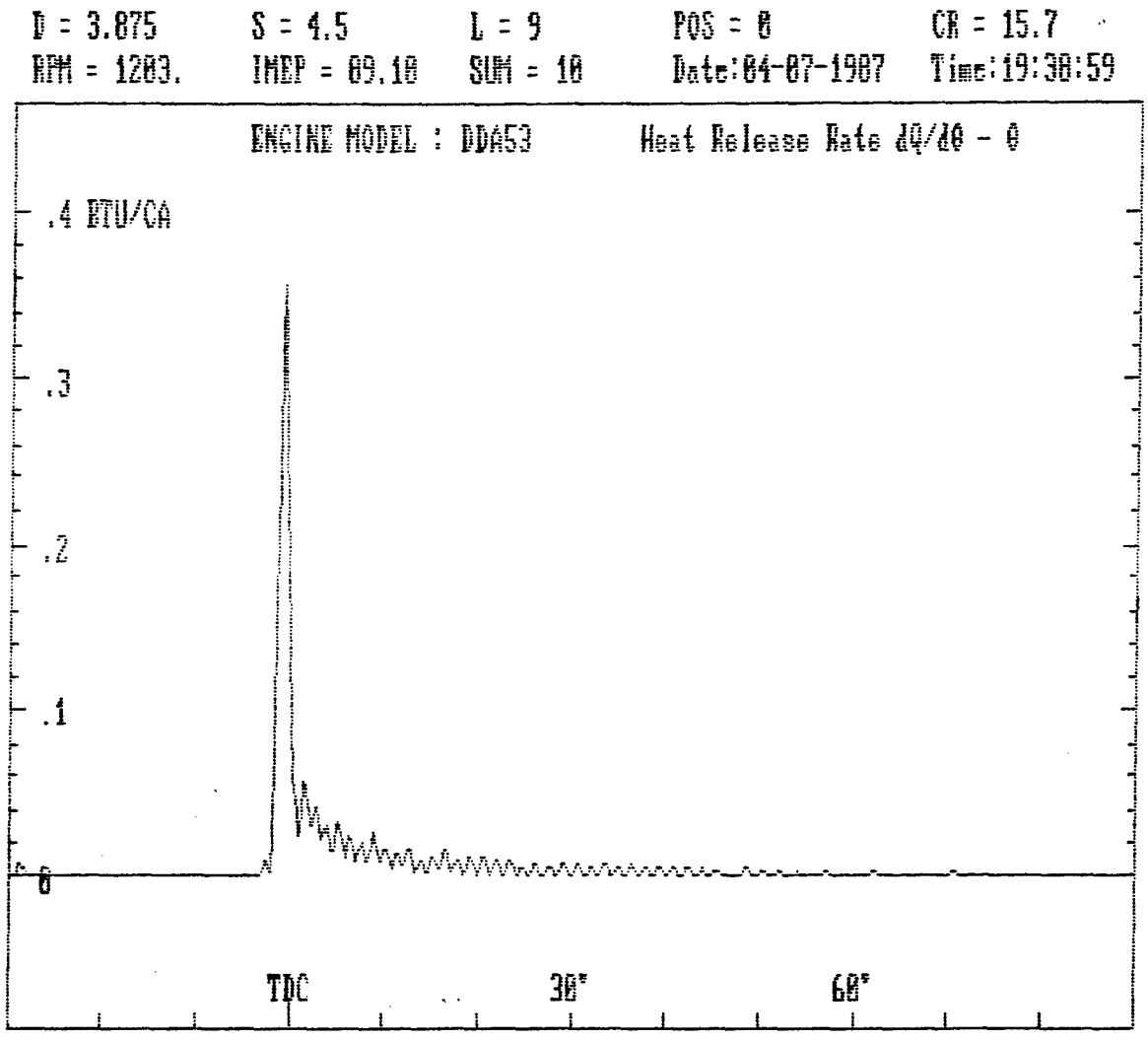
DDA-SR1 8 HOLE, TEST NUMBER 164-1

Test Line	0	1	2	3	4	5
Speed, RPM	1200	1200	1200	1200	1200	1200
Torque, Lb-Ft	-21.8	.1	20	40	50	59
Delivery, mm^3/inj	0	14.5836	27.0839	41.1318	55.4773	60.1203
BMEP, PSI	-31.014	.142264	28.4528	56.9057	71.1321	83.9358
Power, HP	-4.9810	.022848	4.56969	9.13938	11.4242	13.4806
BSFC, Lb/HP-hr	0	85.0267	.789534	.599525	.646897	.594099
Smoke, BSU	0	3	3.2	3.4	5.7	3.8
Boost, psi	3	3	3	3	3	4
Exhaust Pressure, psi	1	1	1	1	1	2
NOx, ppm	0	117.561	302.657	625.325	680.353	627.826
Exhaust Temp. F	0	305	481	583	617	641
Timing, Deg.BTDC	0	11.52	10.08	9	7.2	7.2
Duration, degrees	0	2.88	2.52	2.52	2.52	2.52
Ignition Lag, deg.	0	10.08	8.64	7.56	6.48	6.48

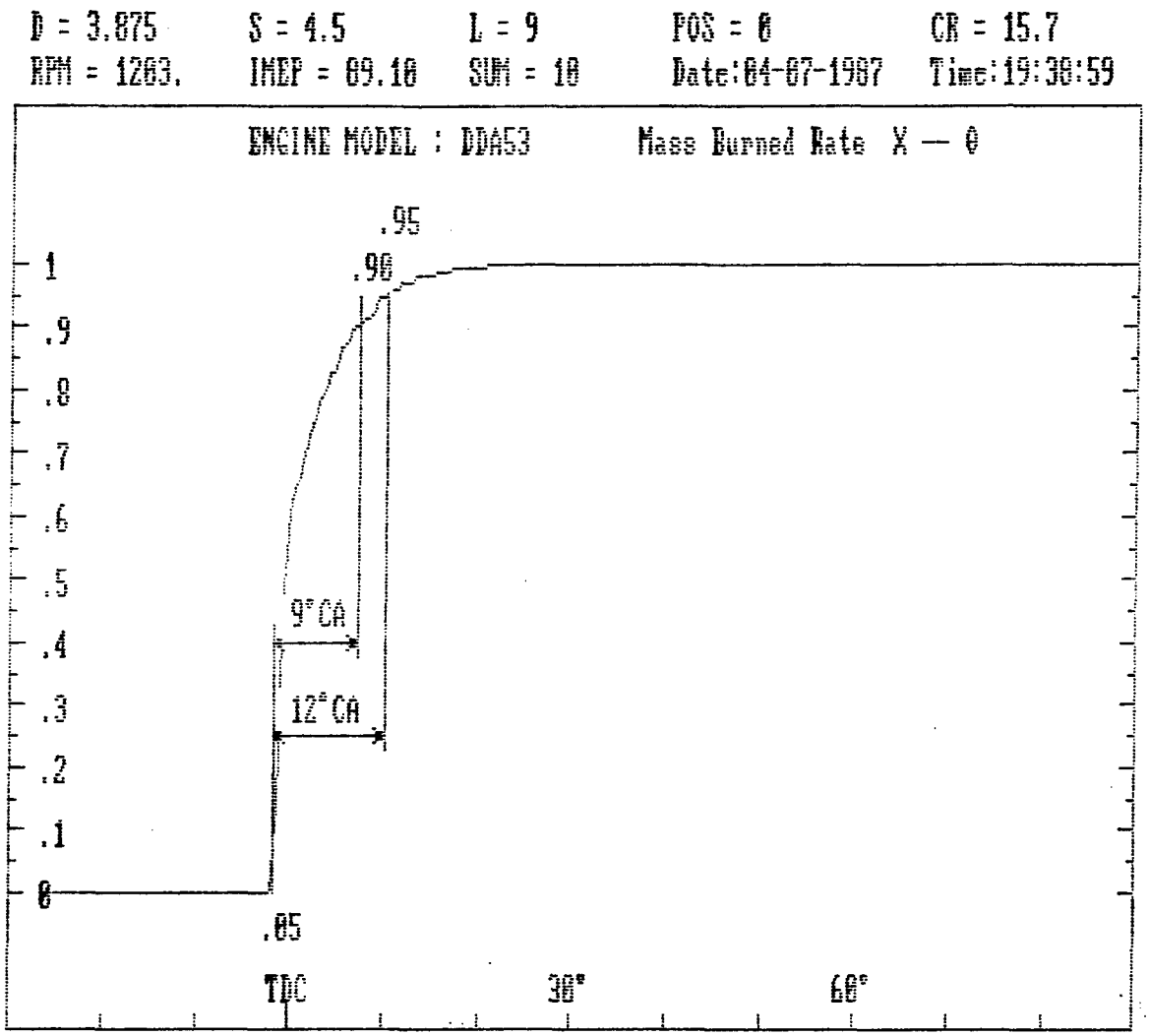
DDA - 53
Servojet Injector
8 Hole Tip
164-1-3



DDA - 53
Servojet Injector
8 Hole Tip
164-1-3



DDA - 53
Servojet Injector
8 Hole Tip
164-1-3

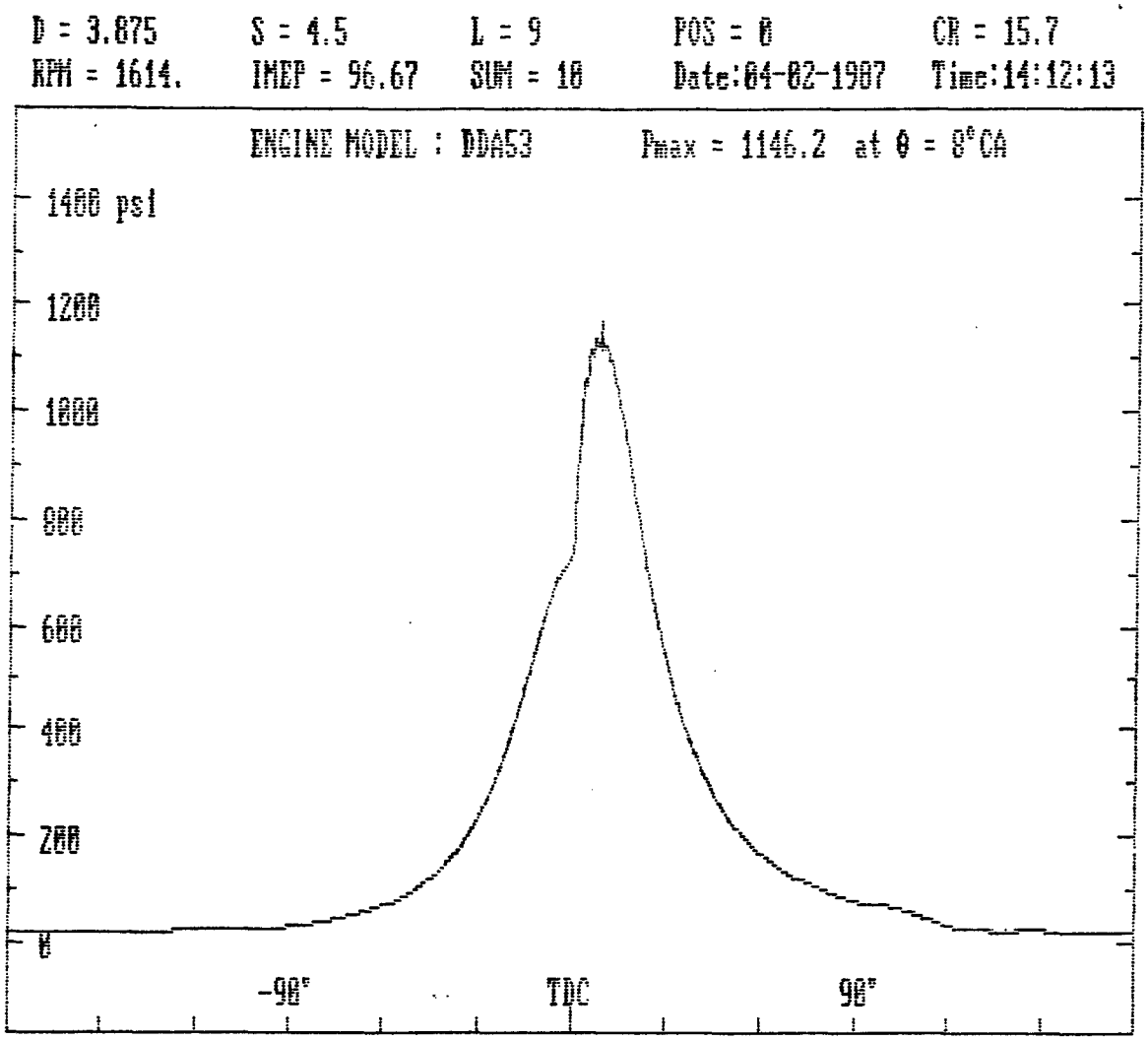


DDA - 53
Servojet Injector
8 Hole Tip
164-1-3

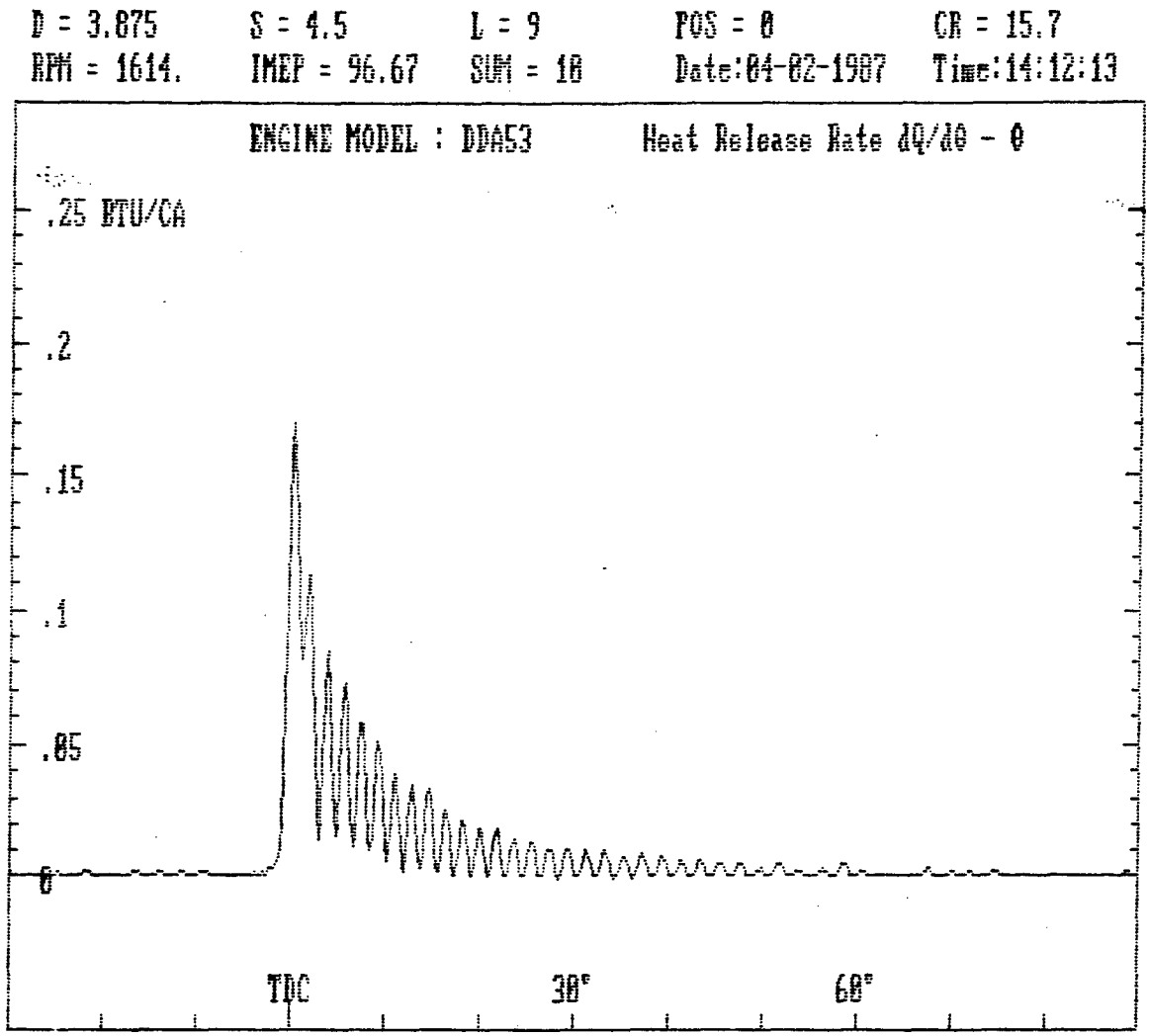
DDA Basline, TEST NUMBER 161-1

Test Line	0	11	12	13	15	14
Speed, RPM	1600	1600	1600	1600	1600	1600
Torque, Lb-Ft	-23	.1	25	40	50	60
Delivery, mm^3/inj	0	14.5405	32.3801	42.6169	51.1617	62.9477
BMEP, PSI	-32.721	.142264	35.5660	56.9057	71.1321	85.3585
Power, HP	-7.0069	.030465	7.61615	12.1858	15.2323	18.2788
BSFC, Lb/HP-hr	0	84.7751	.755141	.621172	.596575	.611672
Smoke, BSU	0	.1	.3	.8	2.4	4.5
Boost, psi	5	5	5	5	5	5
Exhaust Pressure, psi	1.5	1.5	1.5	1.5	1.5	2.5
NOx, ppm	0	200.104	467.743	592.808	710.369	745.387
Exhaust Temp. F	0	271	420	517	625	727
Timing, Deg.BTDC	0	9.12	10.56	11.52	12.48	12.48
Duration, degrees	0	4.32	8.64	9.6	11.04	11.52
Ignition Lag, deg.	0	10.08	11.04	10.56	9.6	8.64

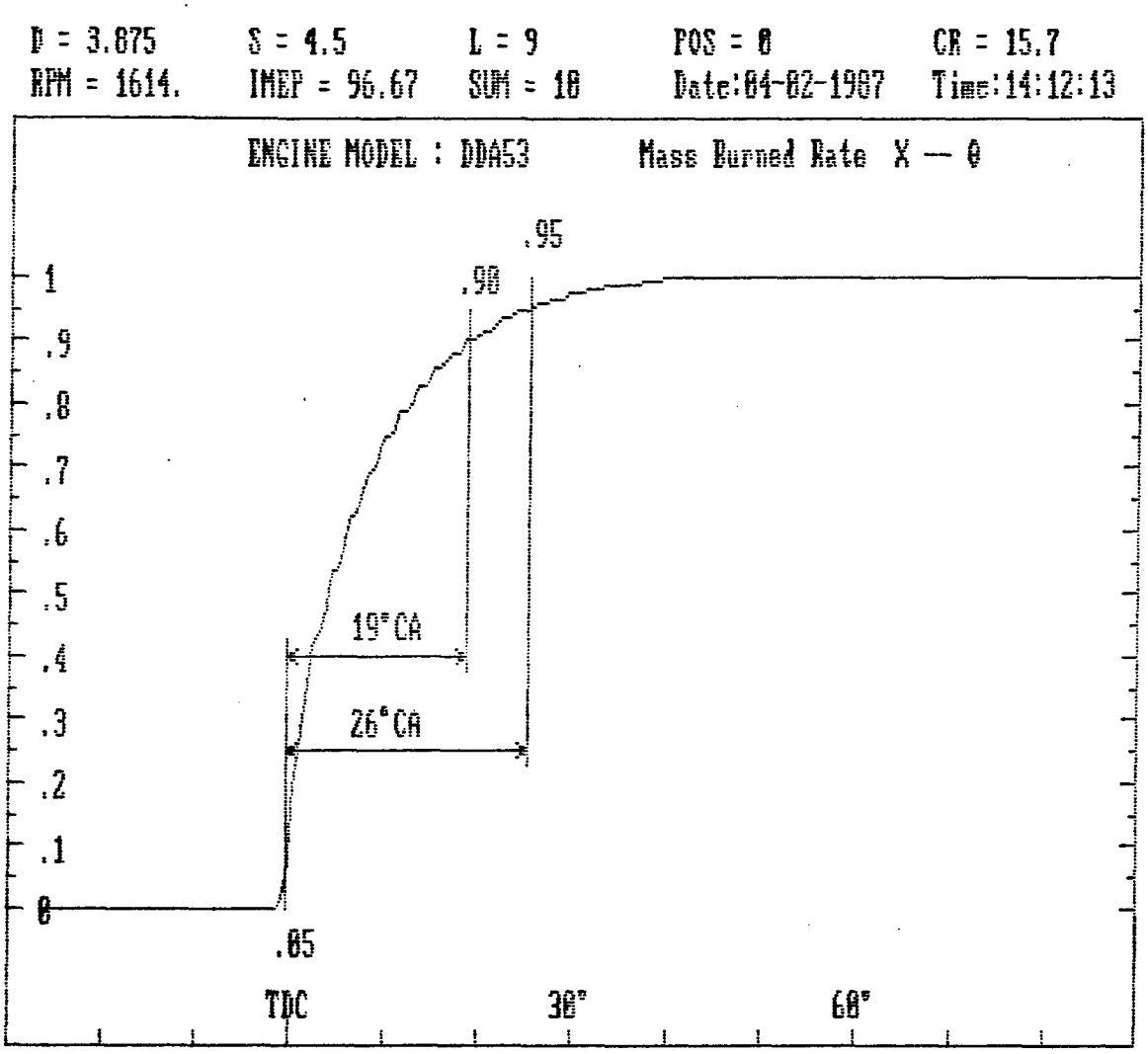
DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-13



DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-13



DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-13

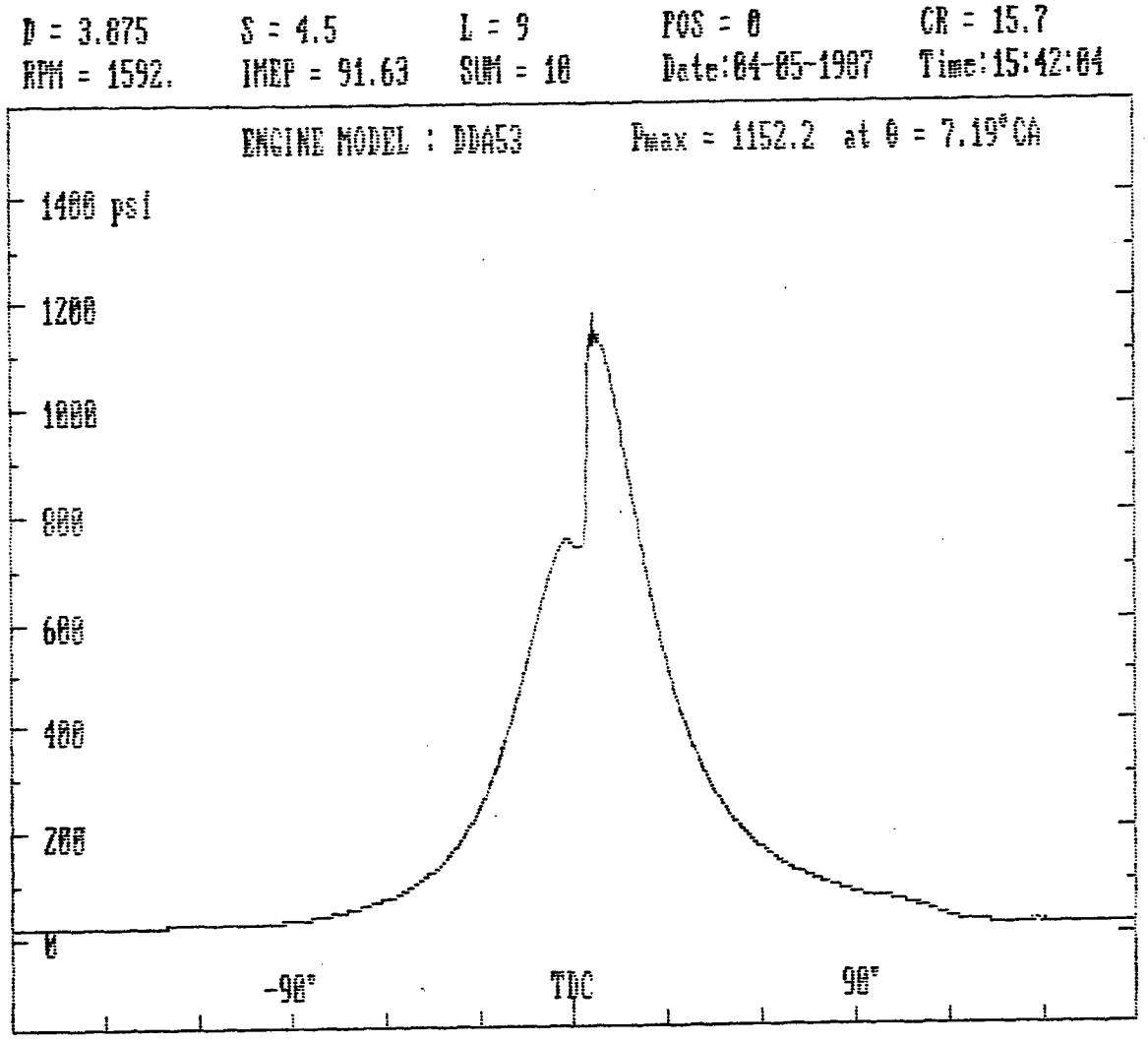


DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-13

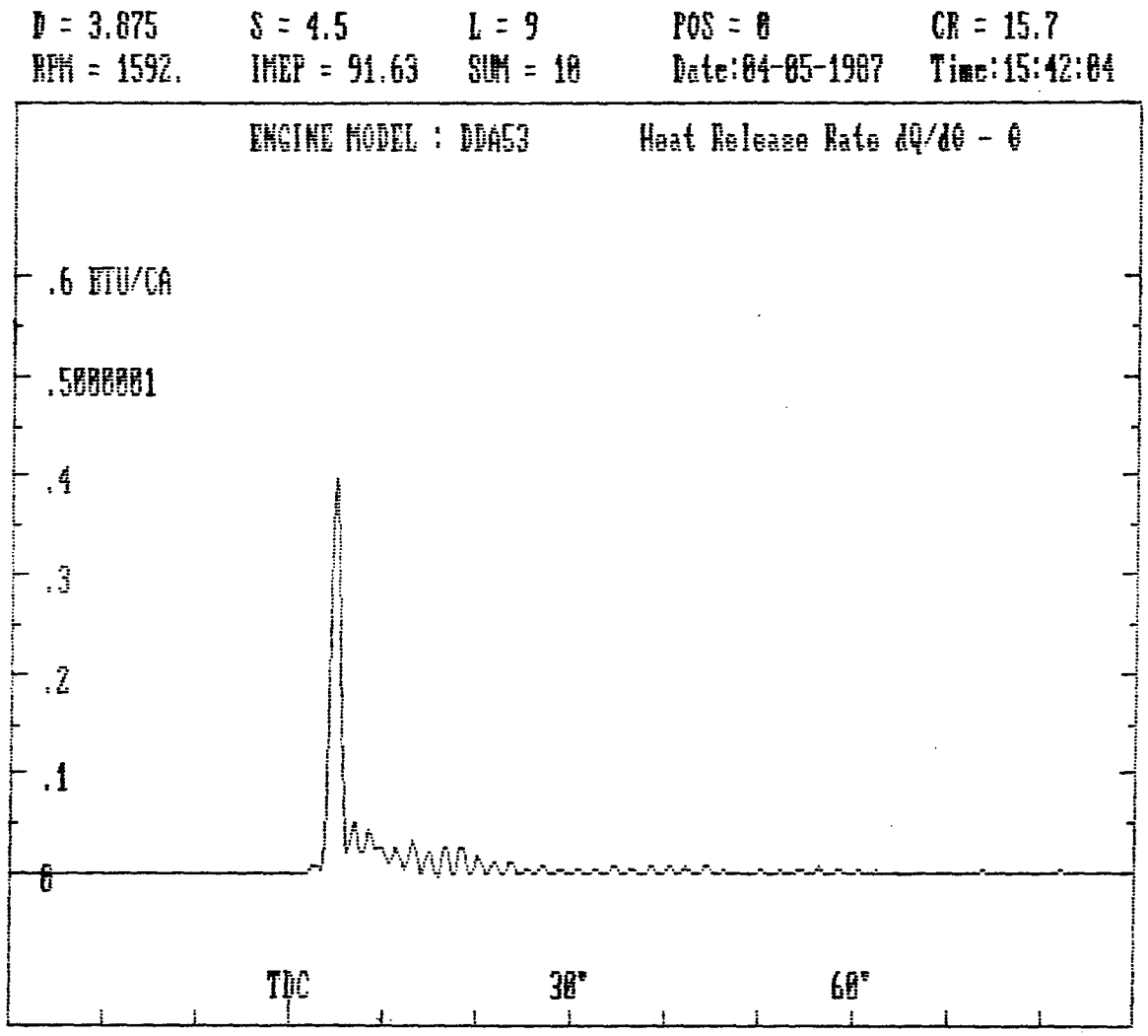
DDA-SR1 12 HOLE, TEST NUMBER 163-1

Test Line	0	5	6	7
Speed, RPM	1600	1600	1600	1600
Torque, Lb-Ft	-23	.1	20	40
Delivery, mm^3/inj	0	17.3218	29.0184	49.5546
BMEP, PSI	-32.721	.142264	28.4528	56.9057
Power, HP	-7.0069	.030465	6.09292	12.1858
BSFC, Lb/HP-hr	0	100.991	.845929	.722293
Smoke, BSU	0	4	5	7.2
Boost, psi	5	5	5	5
Exhaust Pressure, psi	1.5	1.5	1.5	1.5
NOx, ppm	0	87.5455	237.623	372.694
Exhaust Temp. F	0	294	443	598
Timing, Deg.BTDC	0	8.16	7.68	5.76
Duration, degrees	0	3.36	3.84	3.84
Ignition Lag, deg.	0	12	10.08	8.64

DDA - 53
Servojet Injector
12 Hole Tip
163-1-7

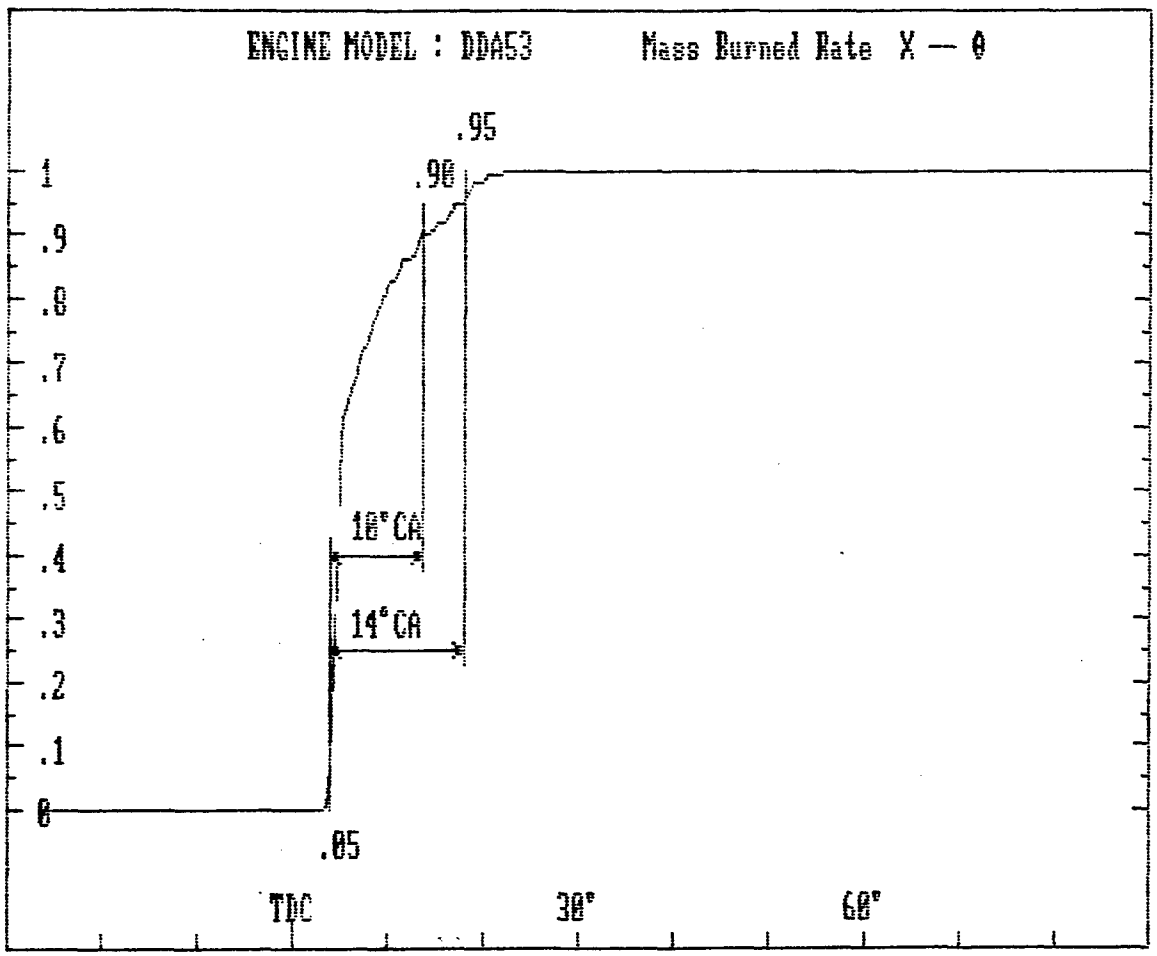


DDA - 53
Servojet Injector
12 Hole Tip
163-1-7



DDA - 53
Servojet Injector
12 Hole Tip
163-1-7

D = 3.875 S = 4.5 L = 9 POS = 0 CR = 15.7
RPM = 1592. IMEP = 91.63 SWI = 10 Date:04-05-1987 Time:15:42:04

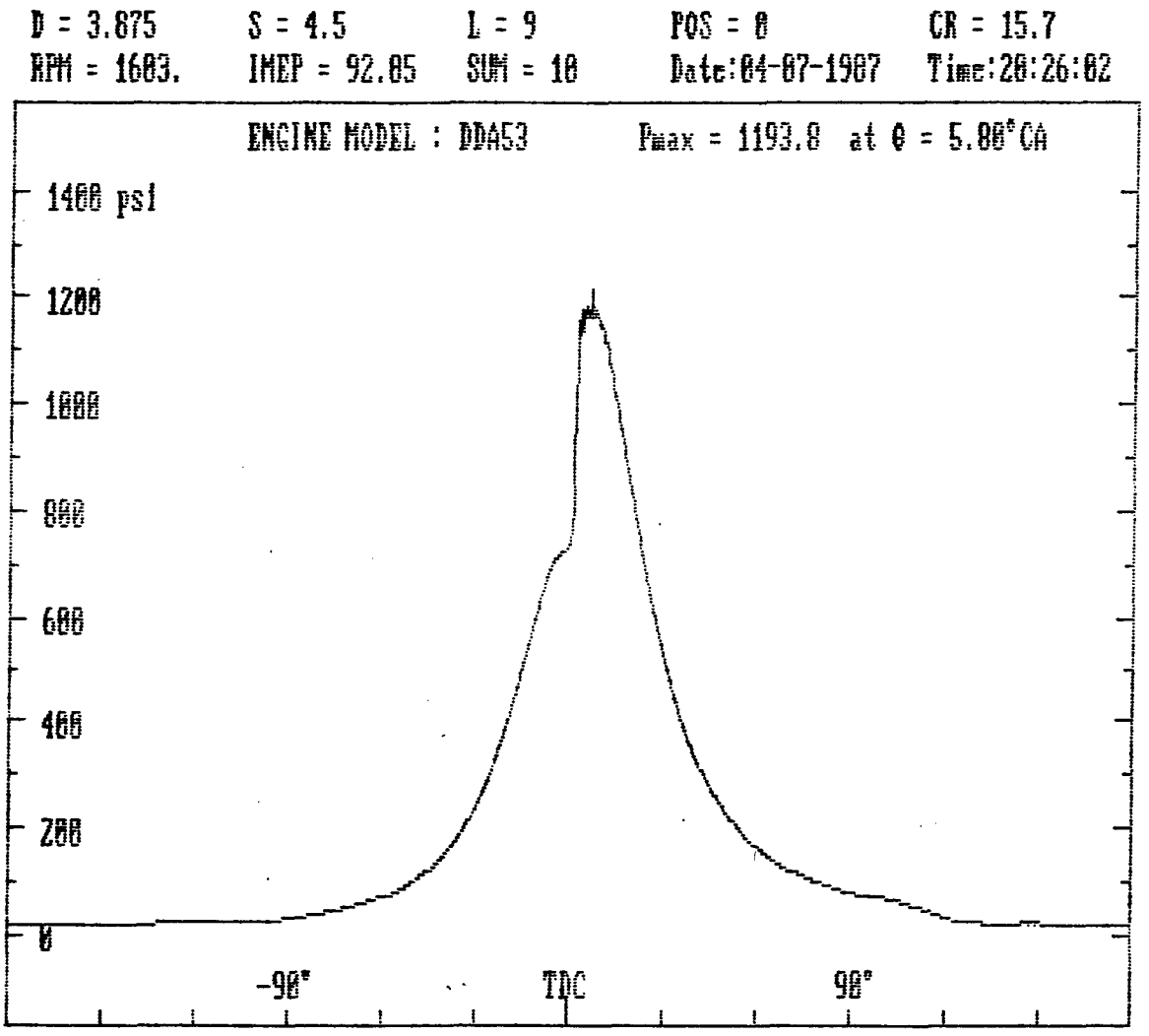


DDA - 53
Servojet Injector
12 Hole Tip
163-1-7

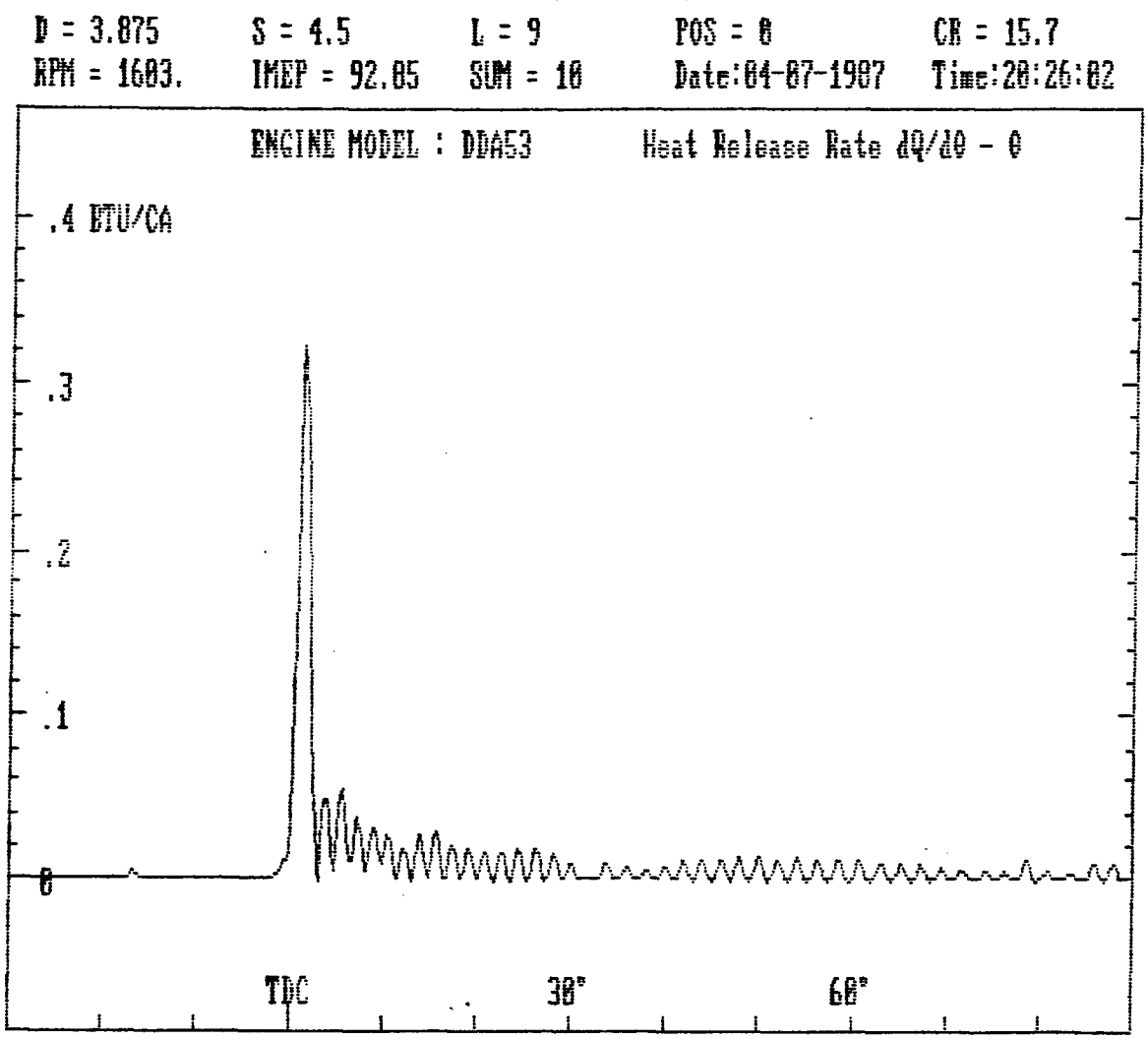
DDA-SR1 8 HOLE, TEST NUMBER 164-1

Test Line	0	6	7	8	9
Speed, RPM	1600	1600	1600	1600	1600
Torque, Lb-Ft	-23	.1	25	40	50
Delivery, mm^3/inj	0	14.7324	34.2418	42.6794	56.9654
BMEP, PSI	-32.721	.142264	35.5660	56.9057	71.1321
Power, HP	-7.0069	.030465	7.61615	12.1858	15.2323
BSFC, Lb/HP-hr	0	85.8943	.798557	.622083	.664249
Smoke, BSU	0	3.2	3.7	4	7
Boost, psi	5	5	5	5	5
Exhaust Pressure, psi	1.5	1.5	1.5	1.5	1.5
NOx, ppm	0	120.062	305.158	450.234	530.275
Exhaust Temp. F	0	281	461	532	684
Timing, Deg.BTDC	0	10.56	9.6	8.64	7.2
Duration, degrees	0	2.88	3.36	3.36	3.36
Ignition Lag, deg.	0	12.48	9.6	8.64	7.2

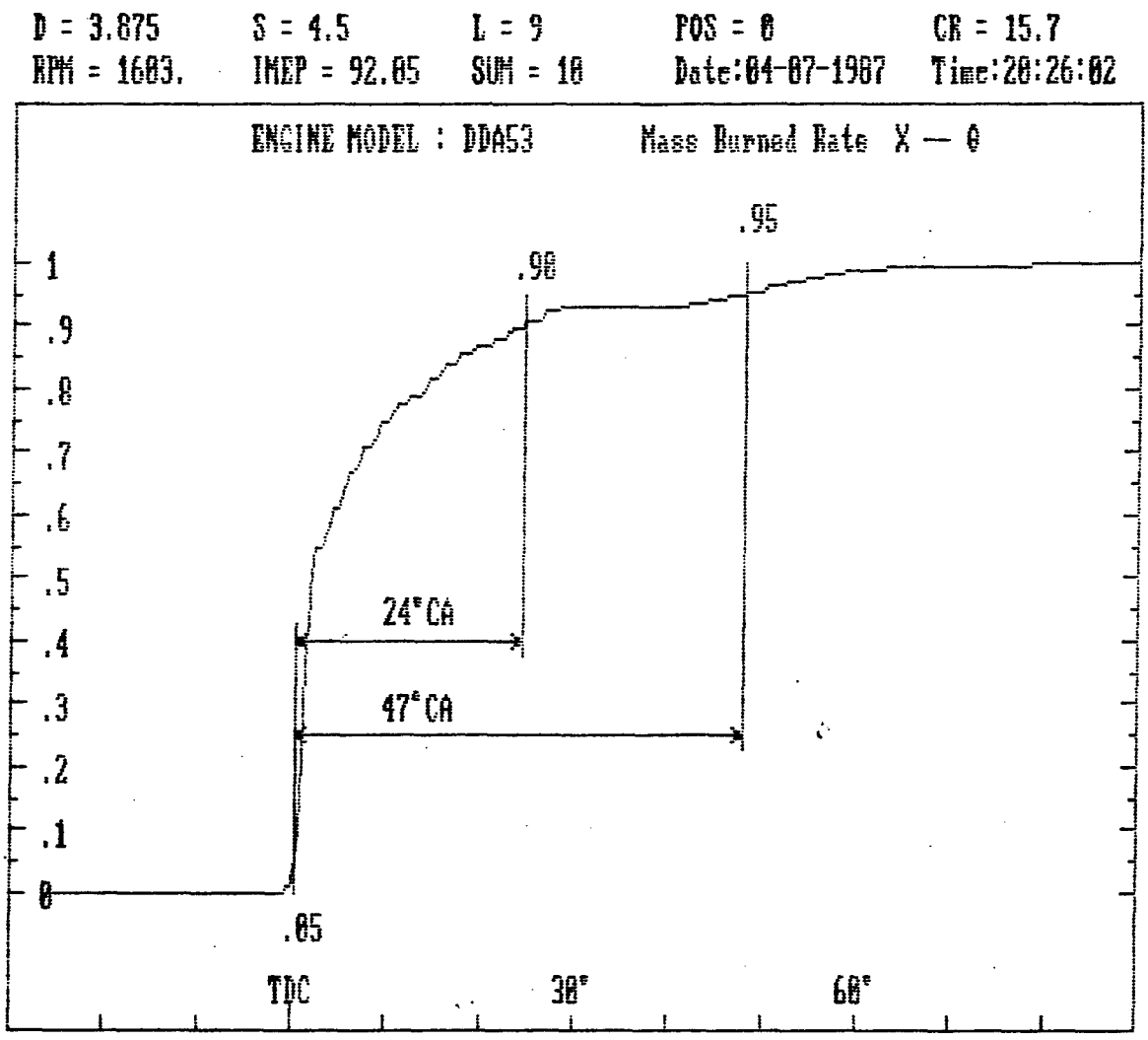
DDA - 53
Servojet Injector
8 Hole Tip
164-1-8



DDA - 53
Servojet Injector
8 Hole Tip
164-1-8



DDA - 53
Servojet Injector
8 Hole Tip
164-1-8

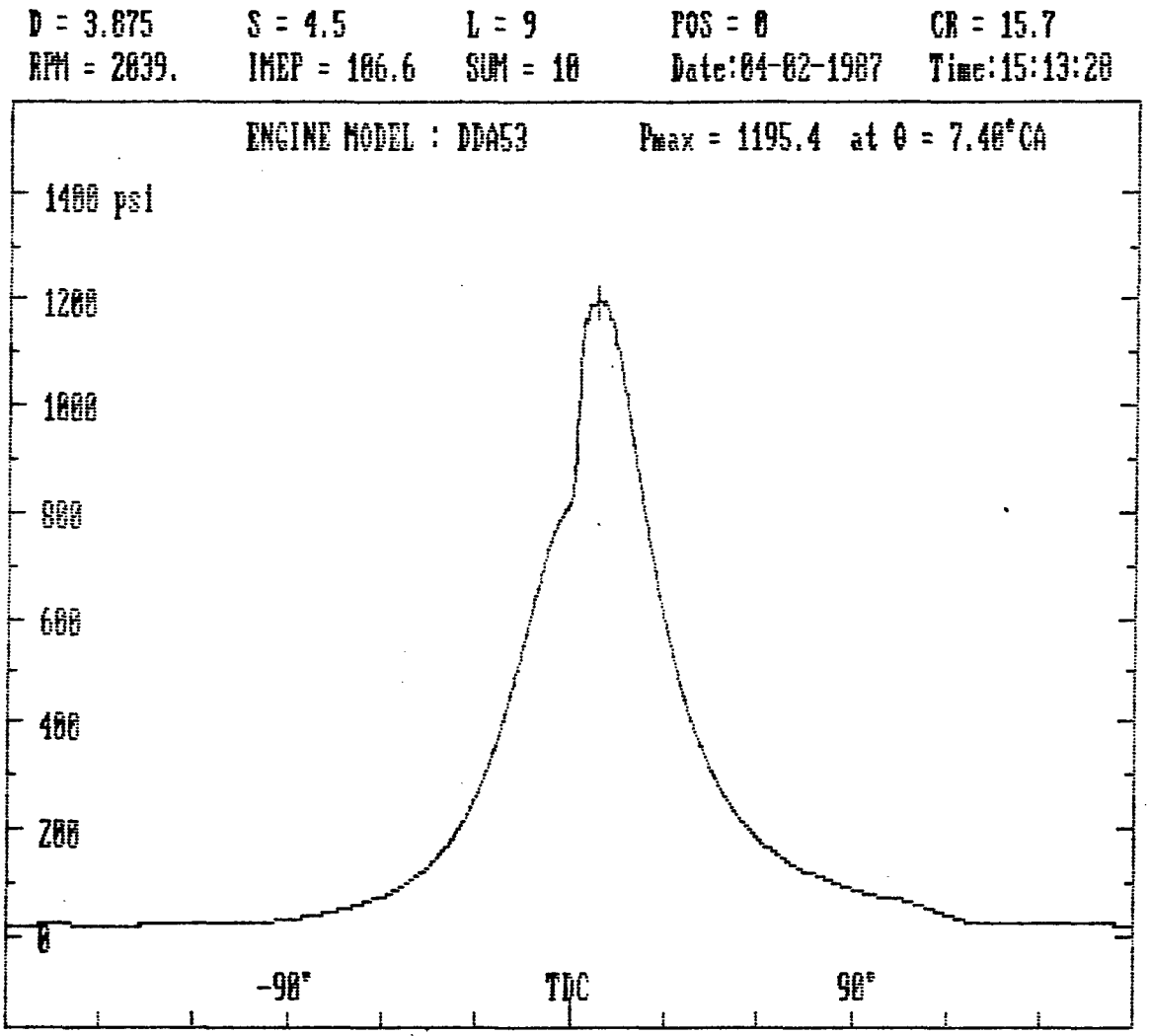


DDA - 53
Servojet Injector
8 Hole Tip
164-1-8

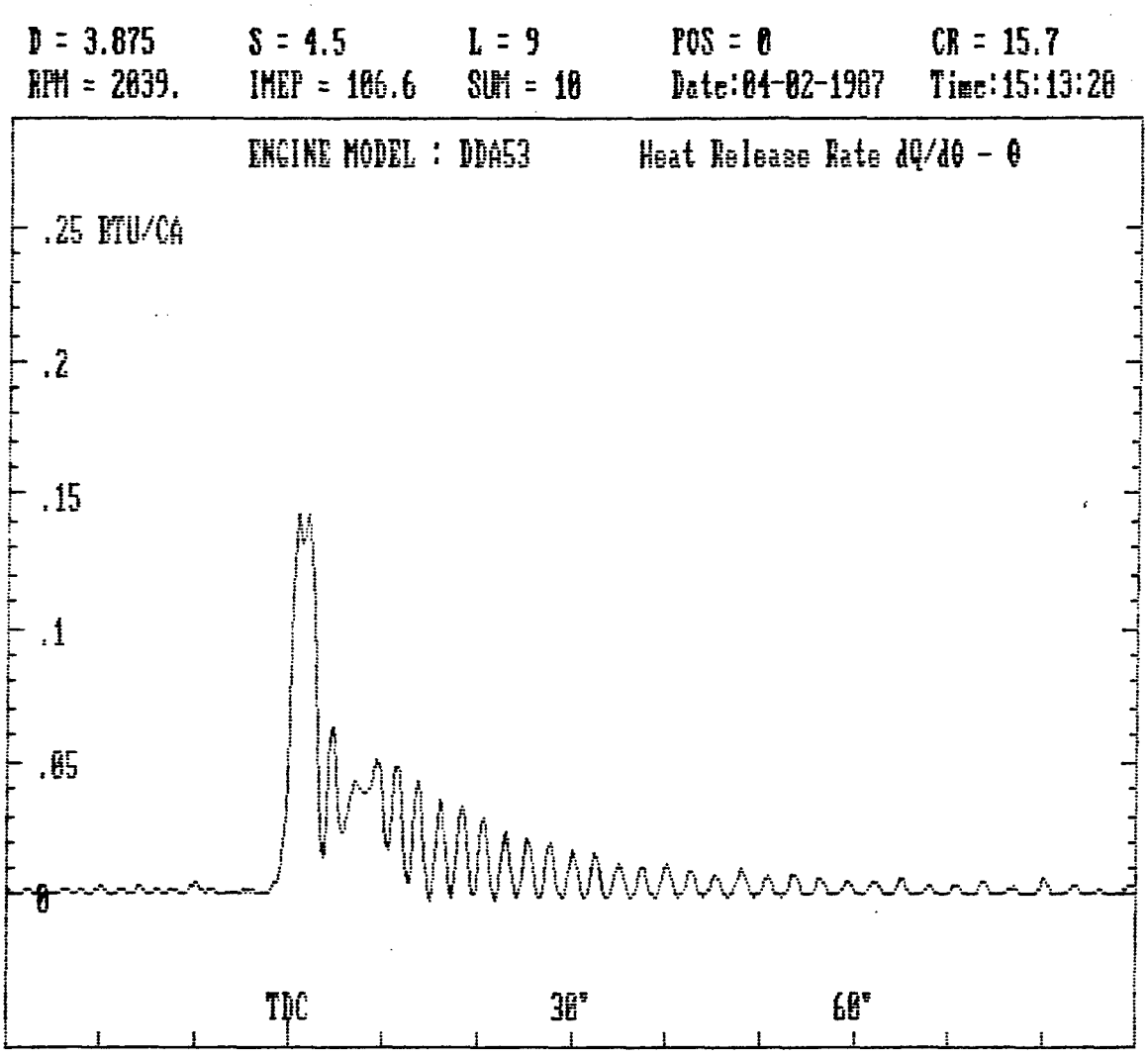
DDA Basline, TEST NUMBER 161-1

Test Line	0	16	17	18	19	20	21
Speed, RPM	2000	2000	2000	2000	2000	2000	2000
Torque, Lb-Ft	-28.1	.1	20	40	50	60	66
Delivery, mm^3/inj	0	16.8218	29.7149	44.9652	50.9653	58.8583	66.1442
BMEP, PSI	-39.976	.142264	28.4528	56.9057	71.1321	85.3585	93.8943
Power, HP	-10.701	.038081	7.61615	15.2323	19.0404	22.8484	25.1333
BSFC, Lb/HP-hr	0	98.0757	.866231	.655400	.594285	.571935	.584302
Smoke, BSU	0	.2	.4	1.2	1.7	2	3.9
Boost, psi	7	7	7	7	7	7	7
Exhaust Pressure, psi	2.5	2.5	2.5	2.5	2.5	2.5	2.5
NOx, ppm	0	167.587	350.182	530.275	630.327	725.377	740.384
Exhaust Temp. F	0	266	390	538	596	662	716
Timing, Deg.BTDC	0	9.6	9.6	10.8	12	13.2	13.2
Duration, degrees	0	5.4	7.2	9.6	12	13.2	13.2
Ignition Lag, deg.	0	12	9.6	10.8	10.8	10.8	10.8

DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-18

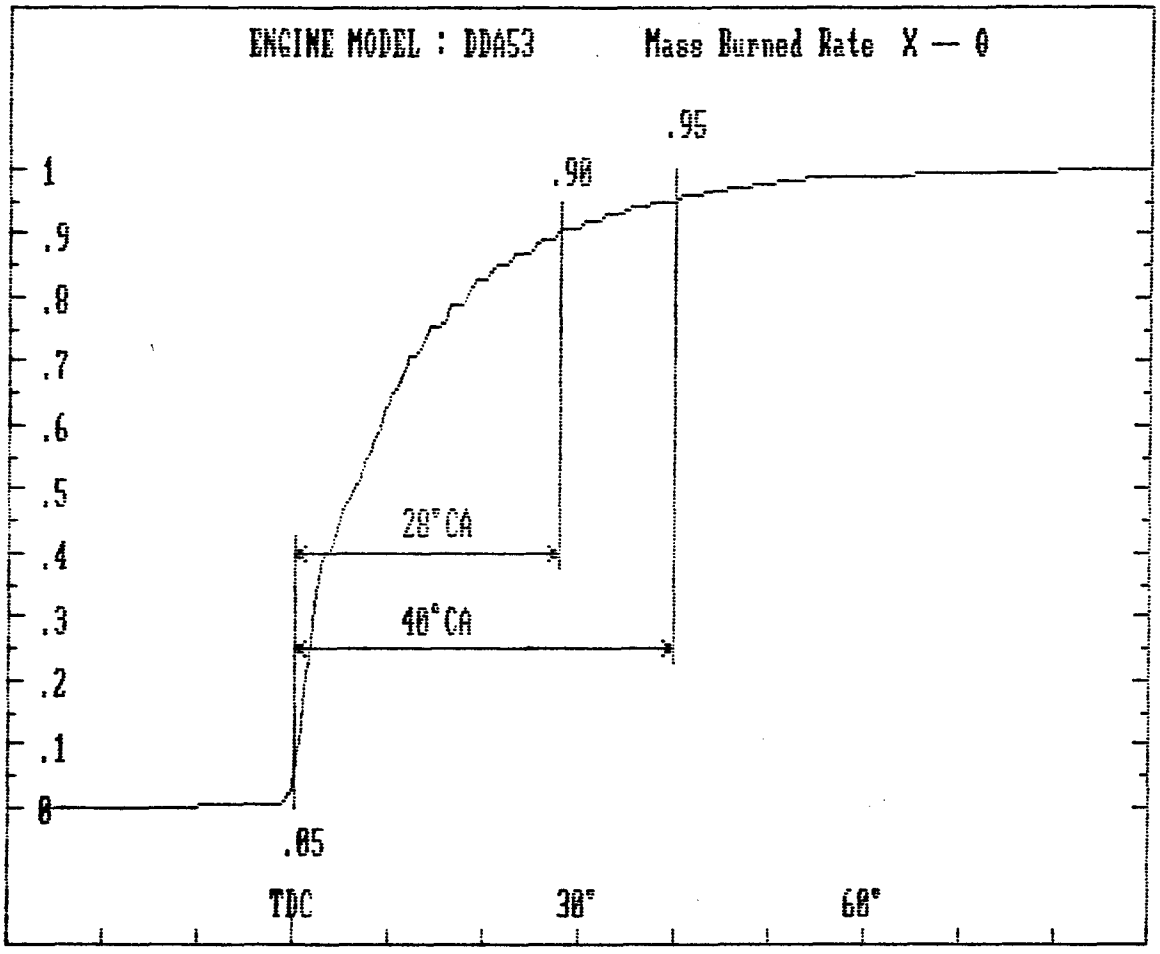


DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-18



DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-18

D = 3.875 S = 4.5 L = 9 POS = 0 CR = 15.7
RPM = 2039. IMEP = 106.6 SUM = 10 Date:04-02-1987 Time:15:13:20

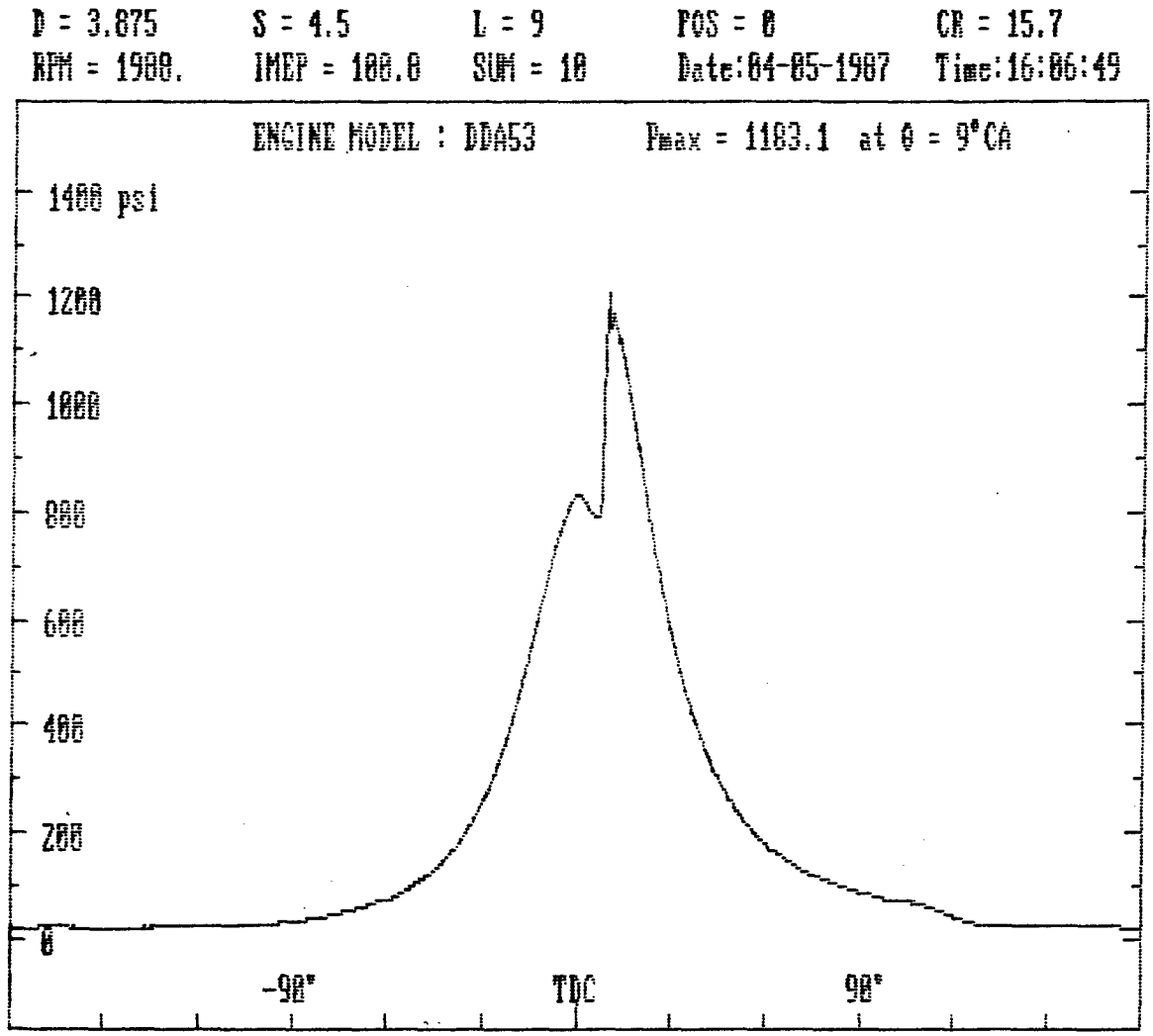


DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-18

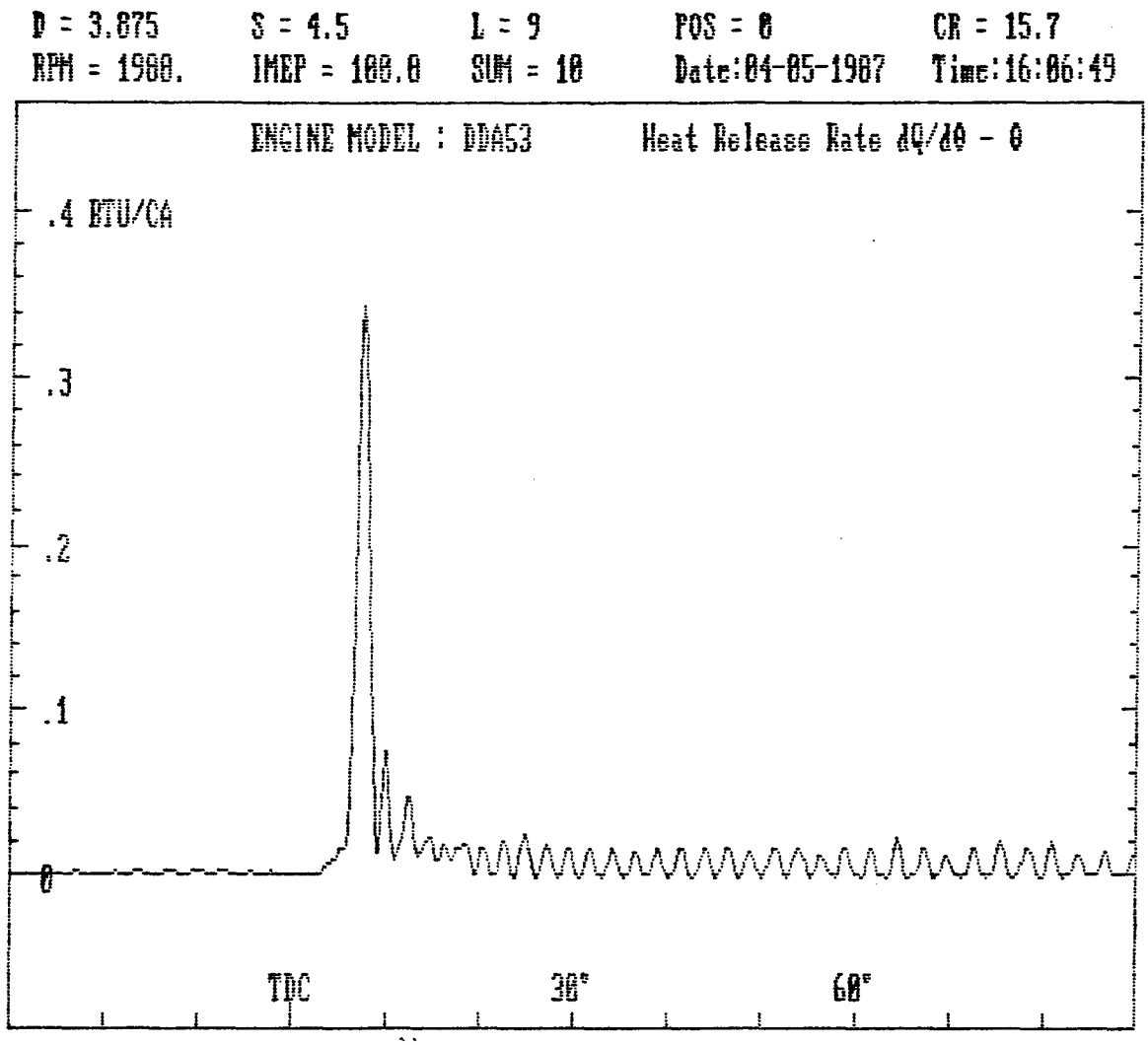
DDA-SR1 12 HOLE, TEST NUMBER 163-1

Test Line	0	9	10	11
Speed, RPM	2000	2000	2000	2000
Torque, Lb-Ft	-28.1	.1	20	40
Delivery, mm^3/inj	0	19.1432	35.5007	52.7153
BMEP, PSI	-39.976	.142264	28.4528	56.9057
Power, HP	-10.701	.038081	7.61615	15.2323
BSFC, Lb/HP-hr	0	111.611	1.03490	.768364
Smoke, BSU	0	3.7	5.5	7.8
Boost, psi	7	7	7	7
Exhaust Pressure, psi	2.5	2.5	2.5	2.5
NOx, ppm	0	67.5351	170.088	307.660
Exhaust Temp. F	0	303	444	561
Timing, Deg.BTDC	0	7.8	6.6	4.8
Duration, degrees	0	4.2	4.2	4.2
Ignition Lag, deg.	0	13.8	11.4	9.6

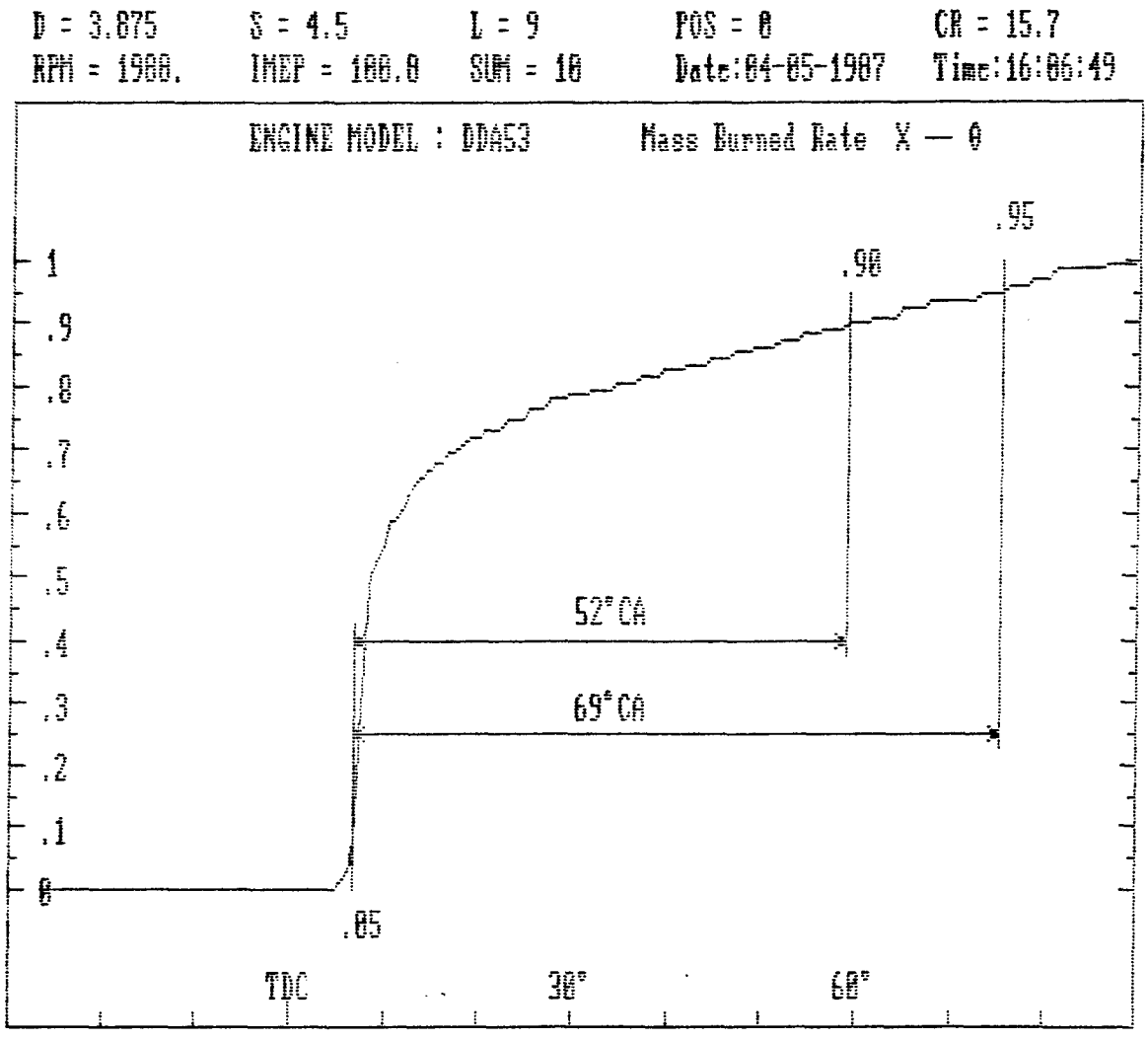
DDA - 53
Servojet Injector
12 Hole Tip
163-1-11



DDA - 53
Servojet Injector
12 Hole Tip
163-1-11



DDA - 53
Servojet Injector
12 Hole Tip
163-1-11

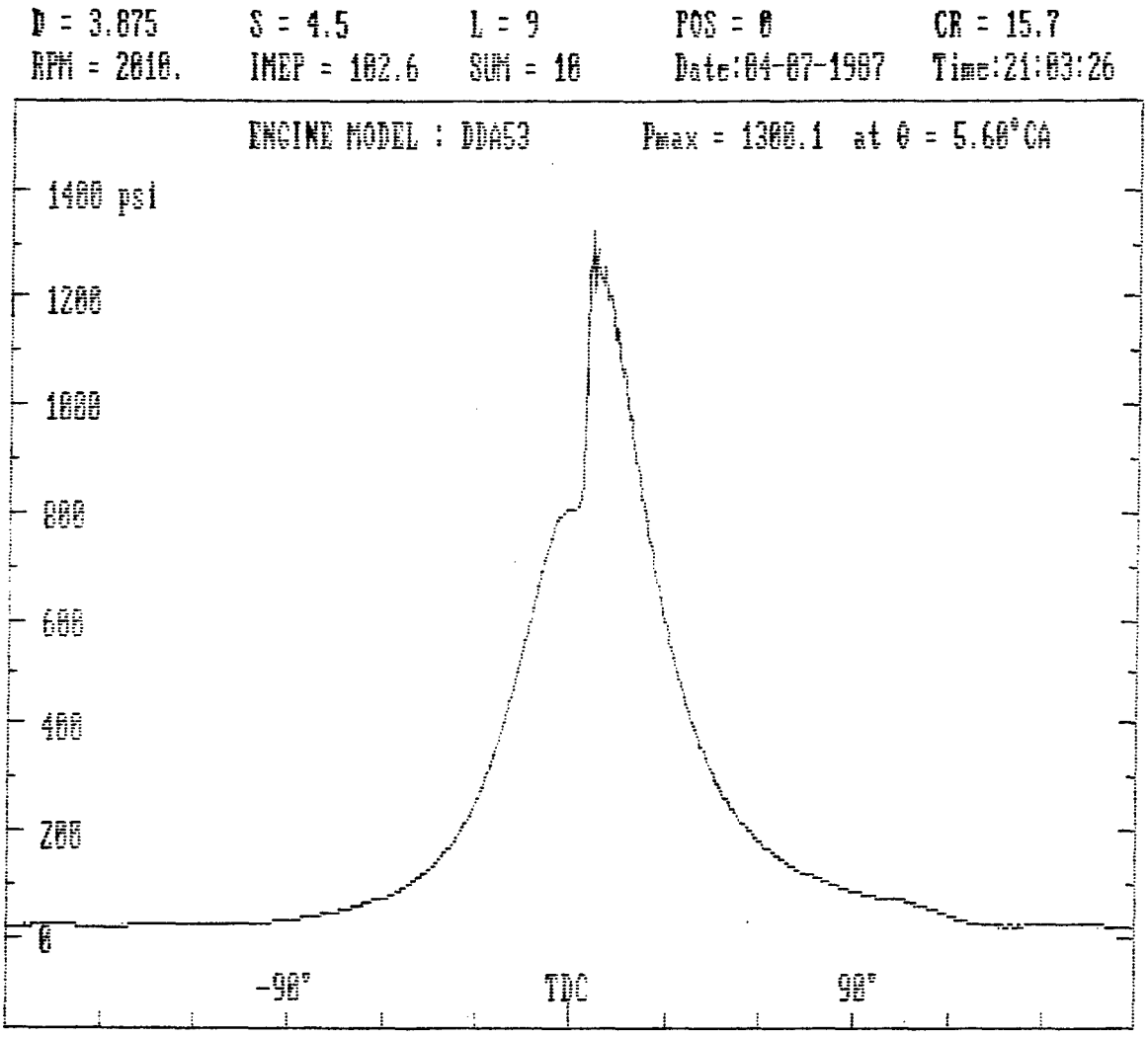


DDA - 53
Servojet Injector
12 Hole Tip
163-1-11

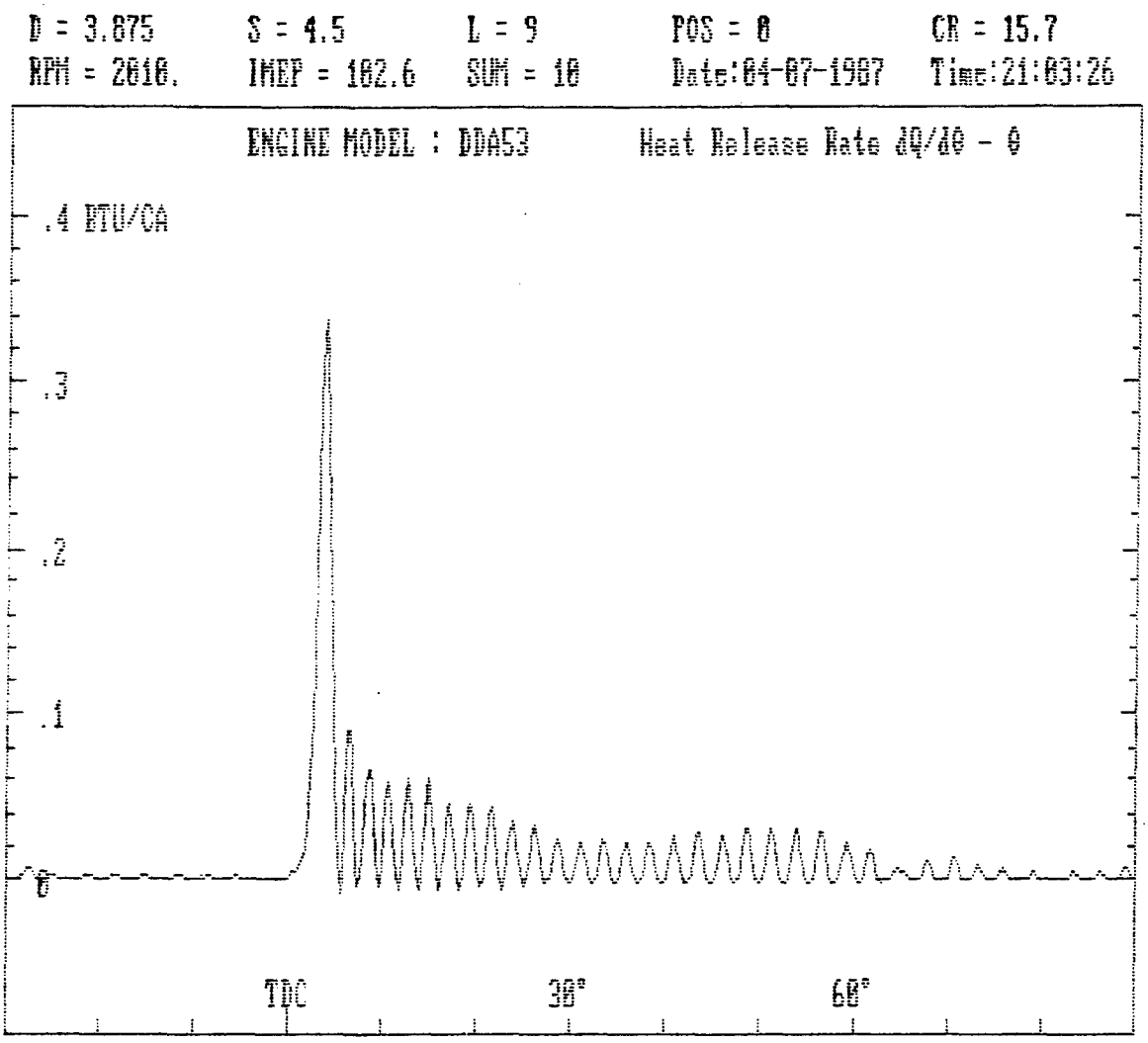
DDA-SR1 8 HOLE, TEST NUMBER 164-1

Test Line	0	10	11	12	13
Speed, RPM	2000	2000	2000	2000	2000
Torque, Lb-Ft	-28.1	.1	20	40	60
Delivery, mm^3/inj	0	22.5719	36.1793	47.5010	69.0728
BMEP, PSI	-39.976	.142264	28.4528	56.9057	85.3585
Power, HP	-10.701	.038081	7.61615	15.2323	22.8484
BSFC, Lb/HP-hr	0	131.601	1.05468	.692360	.671190
Smoke, BSU	0	3.5	4	4.1	7.2
Boost, psi	7	7	7	7	7
Exhaust Pressure, psi	2.5	2.5	2.5	2.5	2.5
NOx, ppm	0	120.062	195.101	390.203	450.234
Exhaust Temp. F	0	323	450	538	676
Timing, Deg.BTDC	0	10.8	9.6	8.4	6.6
Duration, degrees	0	4.8	4.8	4.2	3.6
Ignition Lag, deg.	0	15.6	12	10.8	10.2

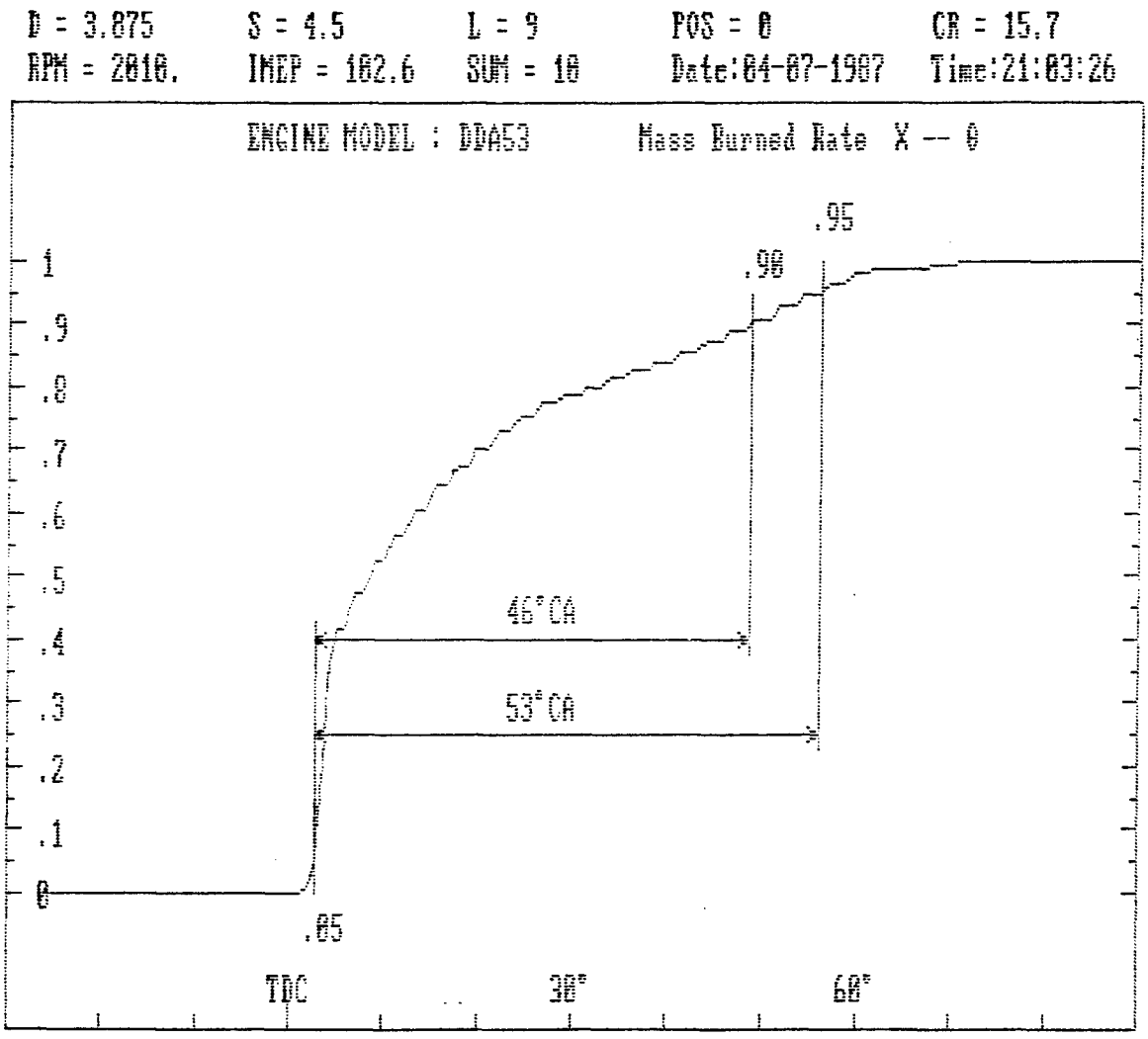
DDA - 53
Servojet Injector
8 Hole Tip
164-1-16



DDA - 53
Servojet Injector
8 Hole Tip
164-1-12



DDA - 53
Servojet Injector
8 Hole Tip
164-1-12

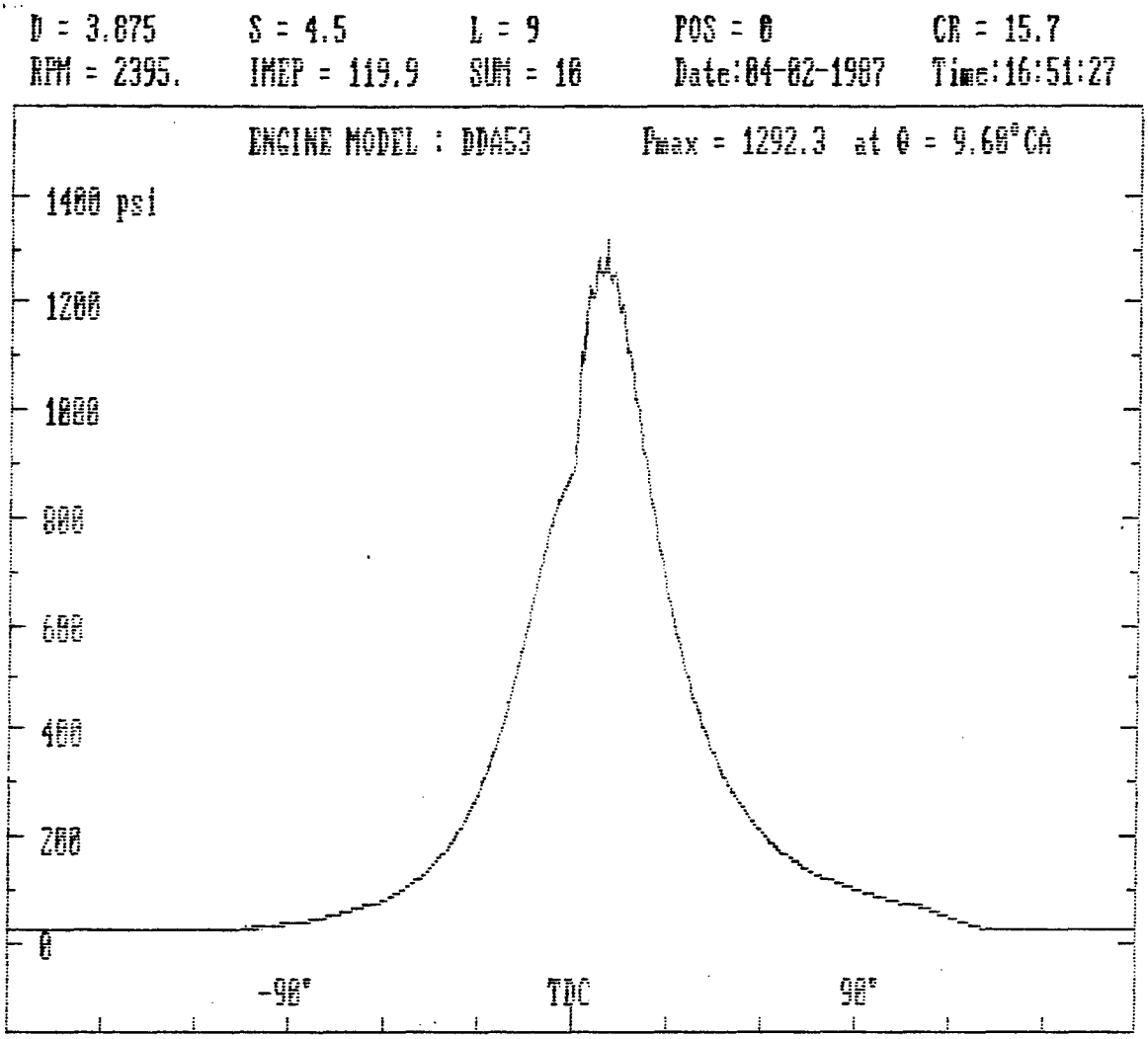


DDA - 53
Servojet Injector
8 Hole Tip
164-1-12

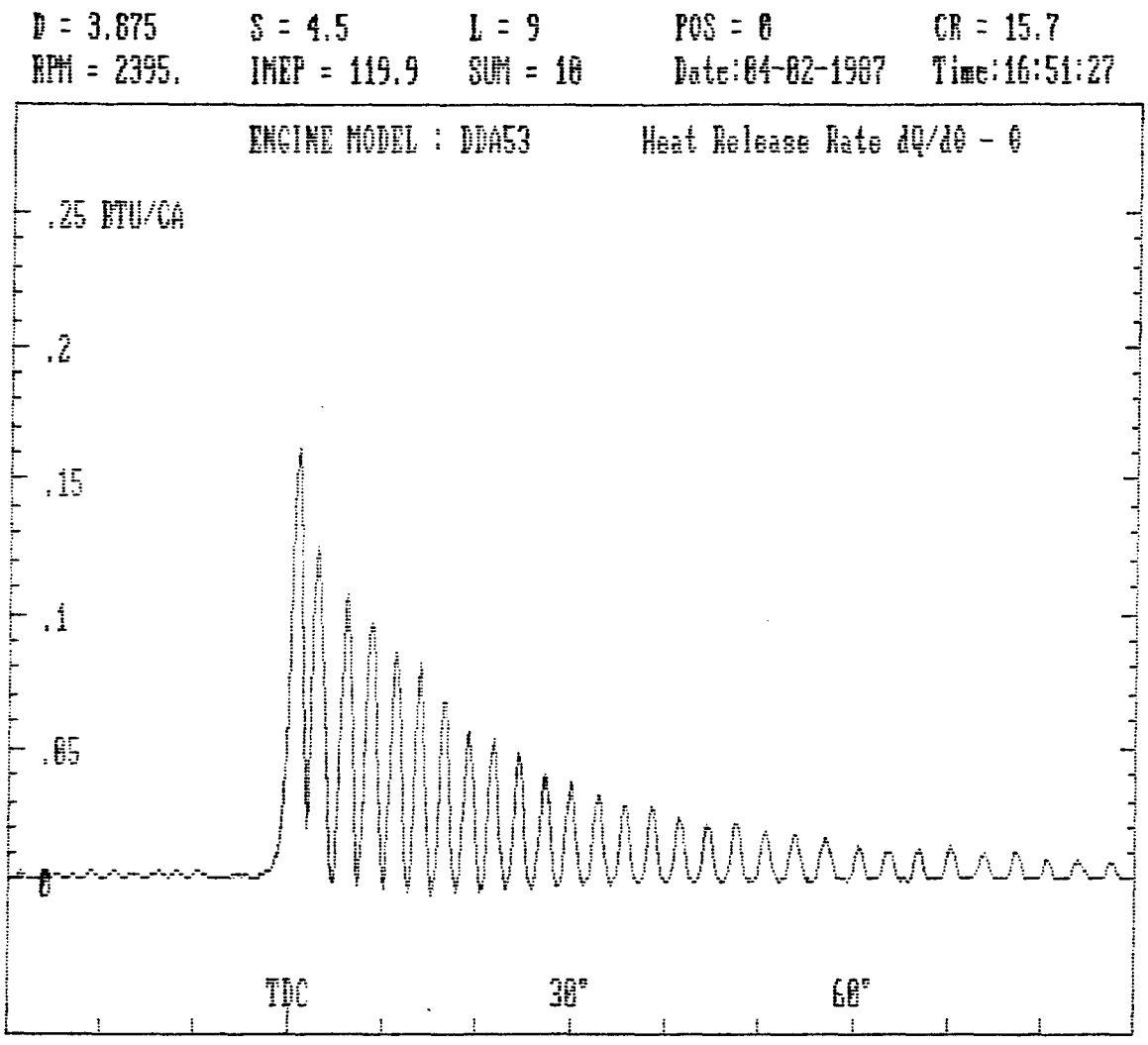
DDA Basline, TEST NUMBER 161-1

Test Line	0	22	23	24	25
Speed, RPM	2400	2400	2400	2400	2400
Torque, Lb-Ft	-33.9	5.5	20	50	60
Delivery, mm^3/inj	0	20.3129	29.9113	52.3522	63.6322
BMEP, PSI	-48.228	7.82453	28.4528	71.1321	85.3585
Power, HP	-15.491	2.51333	9.13938	22.8484	27.4181
BSFC, Lb/HP-hr	0	2.15327	.871958	.610457	.618323
Smoke, BSU	0	.4	.4	1.2	2.5
Boost, psi	10	10	10.5	10	10.5
Exhaust Pressure, psi	3.5	3.5	3.5	3.5	3.5
NOx, ppm	0	165.086	277.644	502.761	597.810
Exhaust Temp. F	0	307	395	618	750
Timing, Deg.BTDC	0	10.08	10.08	12.24	12.96
Duration, degrees	0	7.2	7.2	12.24	12.24
Ignition Lag, deg.	0	10.08	7.2	6.48	2.88

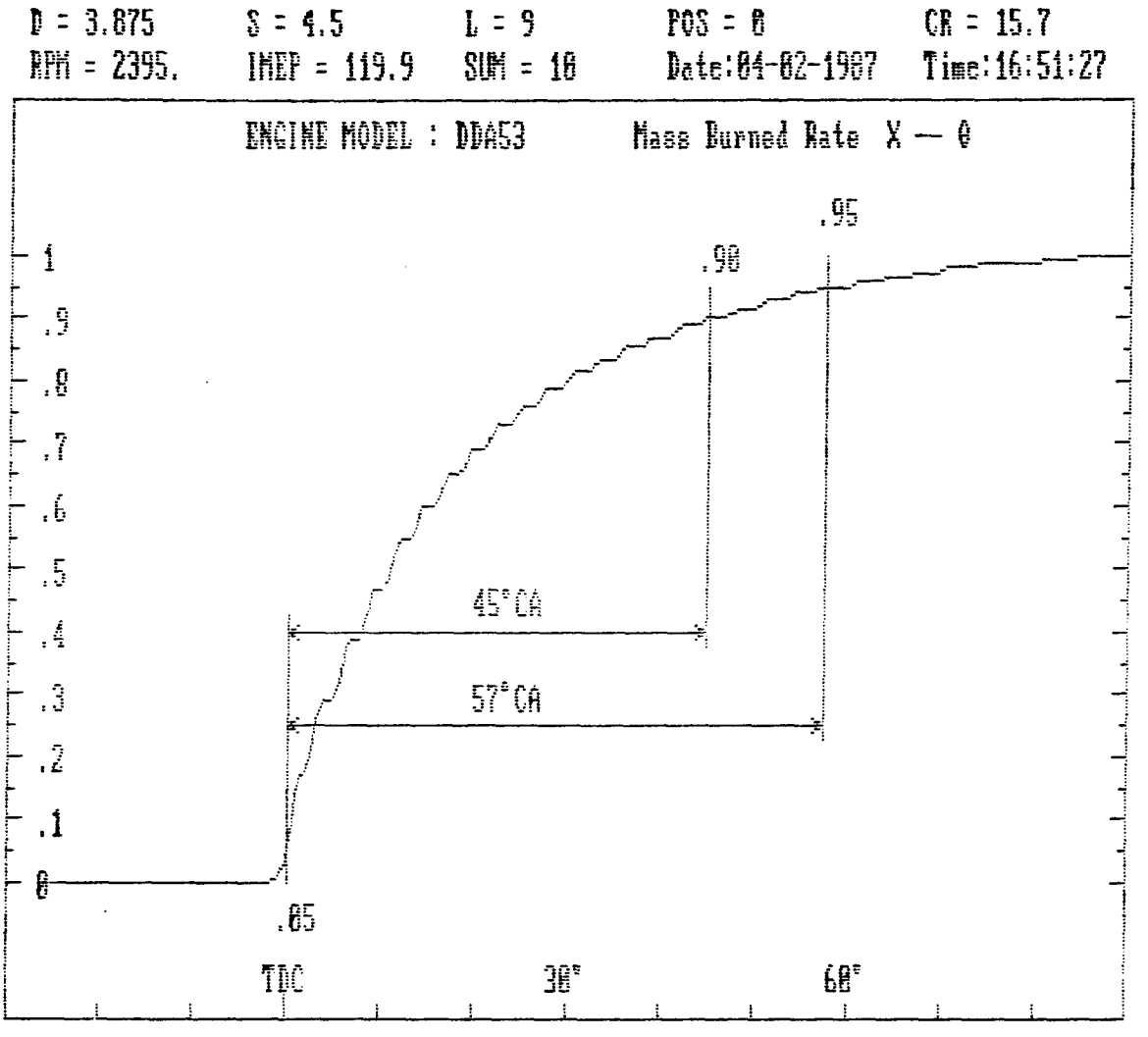
DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-24



DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-24



DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-24

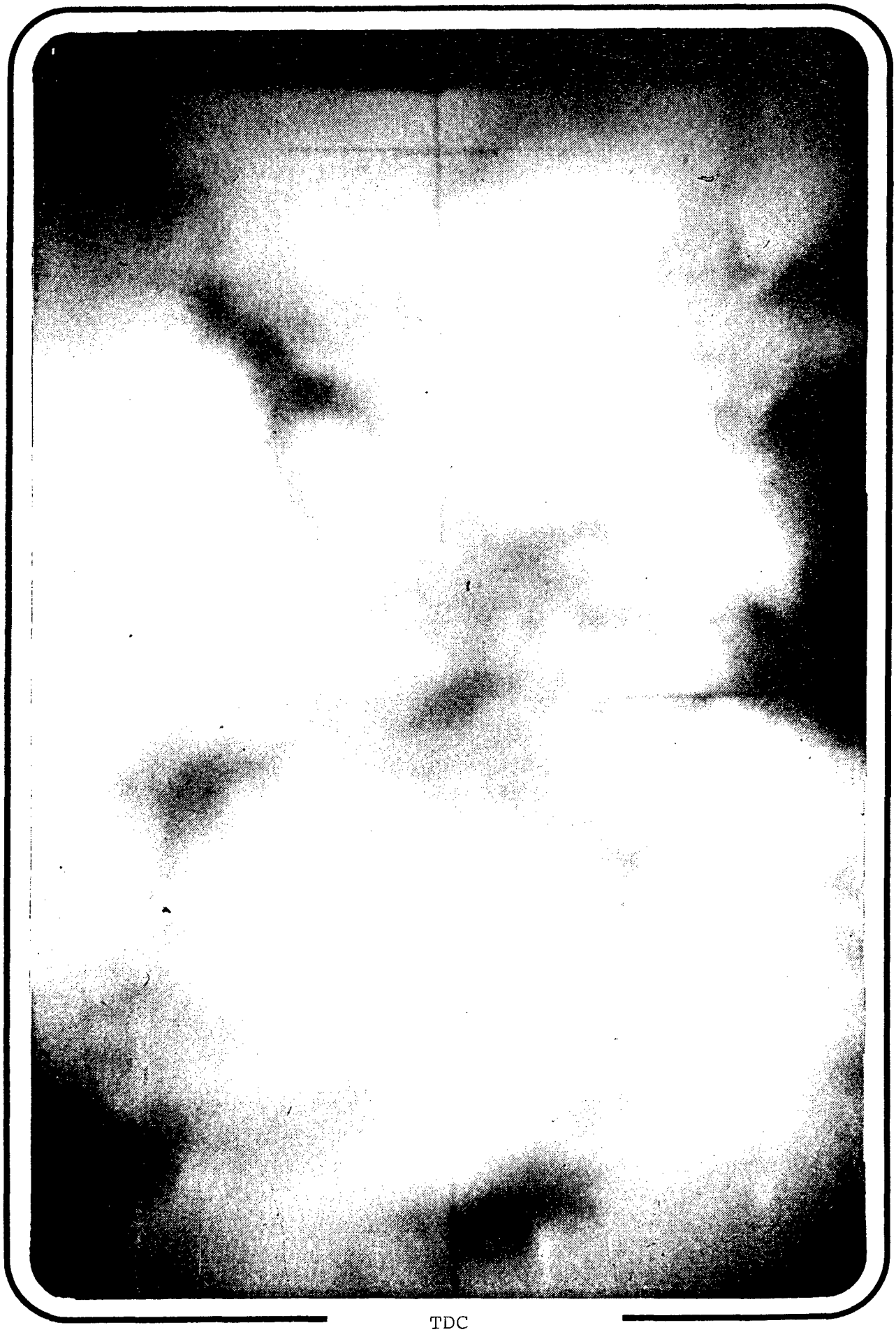


DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-24

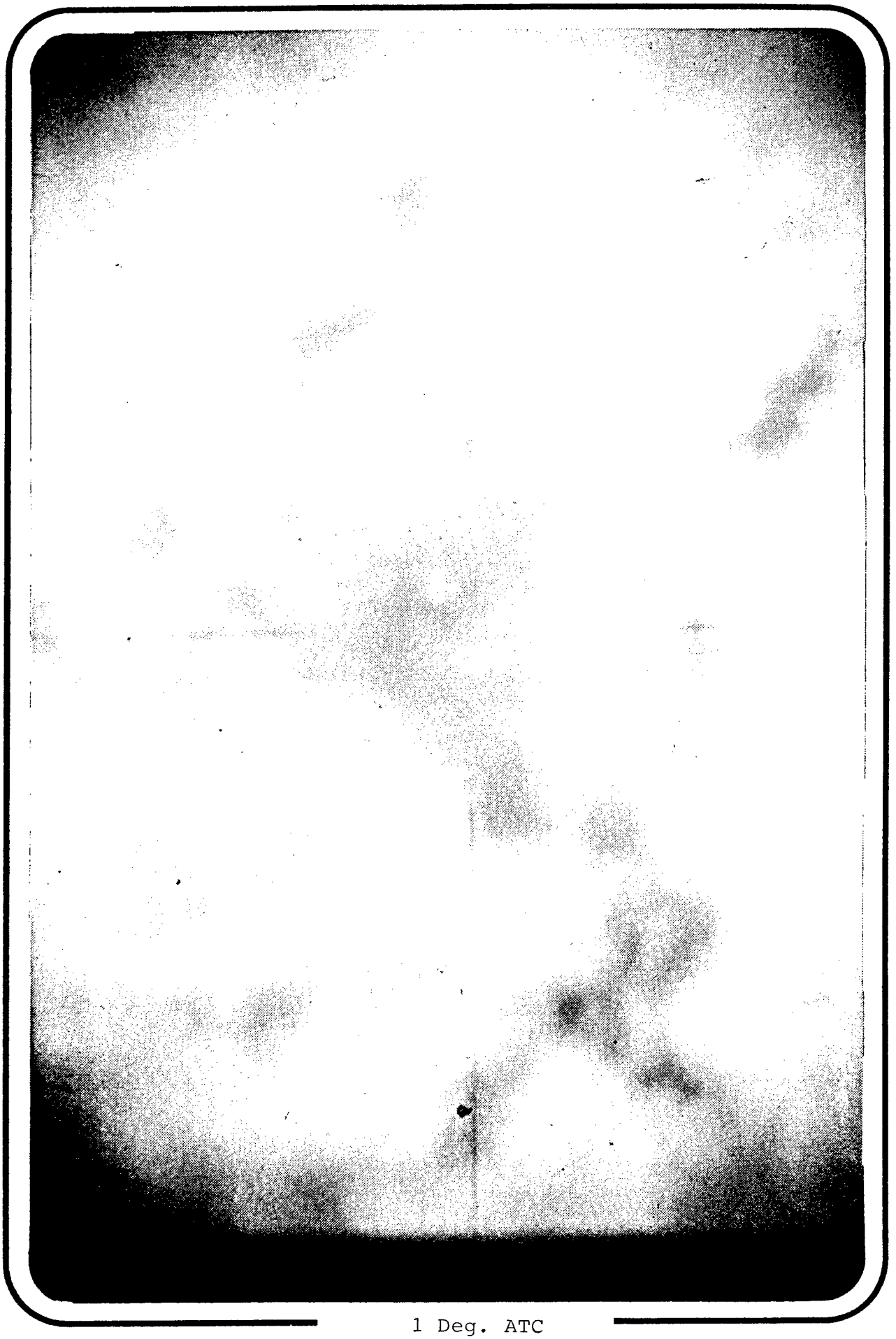
DDA-SR1 8 HOLE, TREST NUMBER 164-1

Test Line	0	14	15	16
Speed, RPM	2400	2400	2400	2400
Torque, Lb-Ft	-33.9	5.5	20	50
Delivery, mm^3/inj	0	29.0482	37.7389	66.6085
BMEP, PSI	-48.228	7.82453	28.4528	71.1321
Power, HP	-15.491	2.51333	9.13938	22.8484
BSFC, Lb/HP-hr	0	3.07926	1.10014	.776693
Smoke, BSU	0	4.2	4.7	7.5
Boost, psi	10	10	10	10
Exhaust Pressure, psi	3.5	3.5	3.5	3.5
NOx, ppm	0	117.561	172.590	342.678
Exhaust Temp. F	0	408	481	711
Timing, Deg.BTDC	0	10.08	9.36	7.92
Duration, degrees	0	5.76	5.04	6.48
Ignition Lag, deg.	0	15.84	13.68	12.24

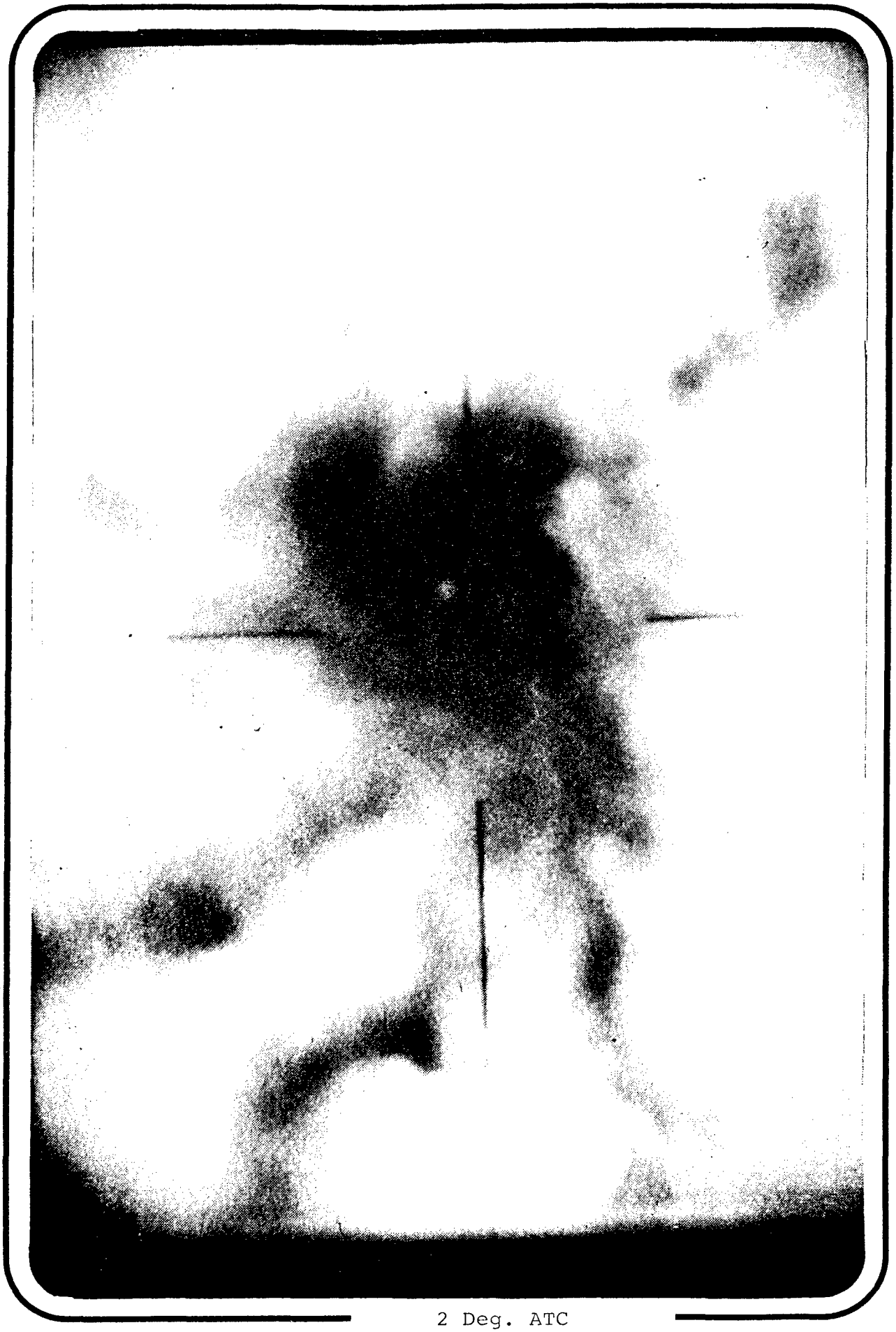
DDA - 53
Servojet Injector
8 Hole Tip
164-1-12



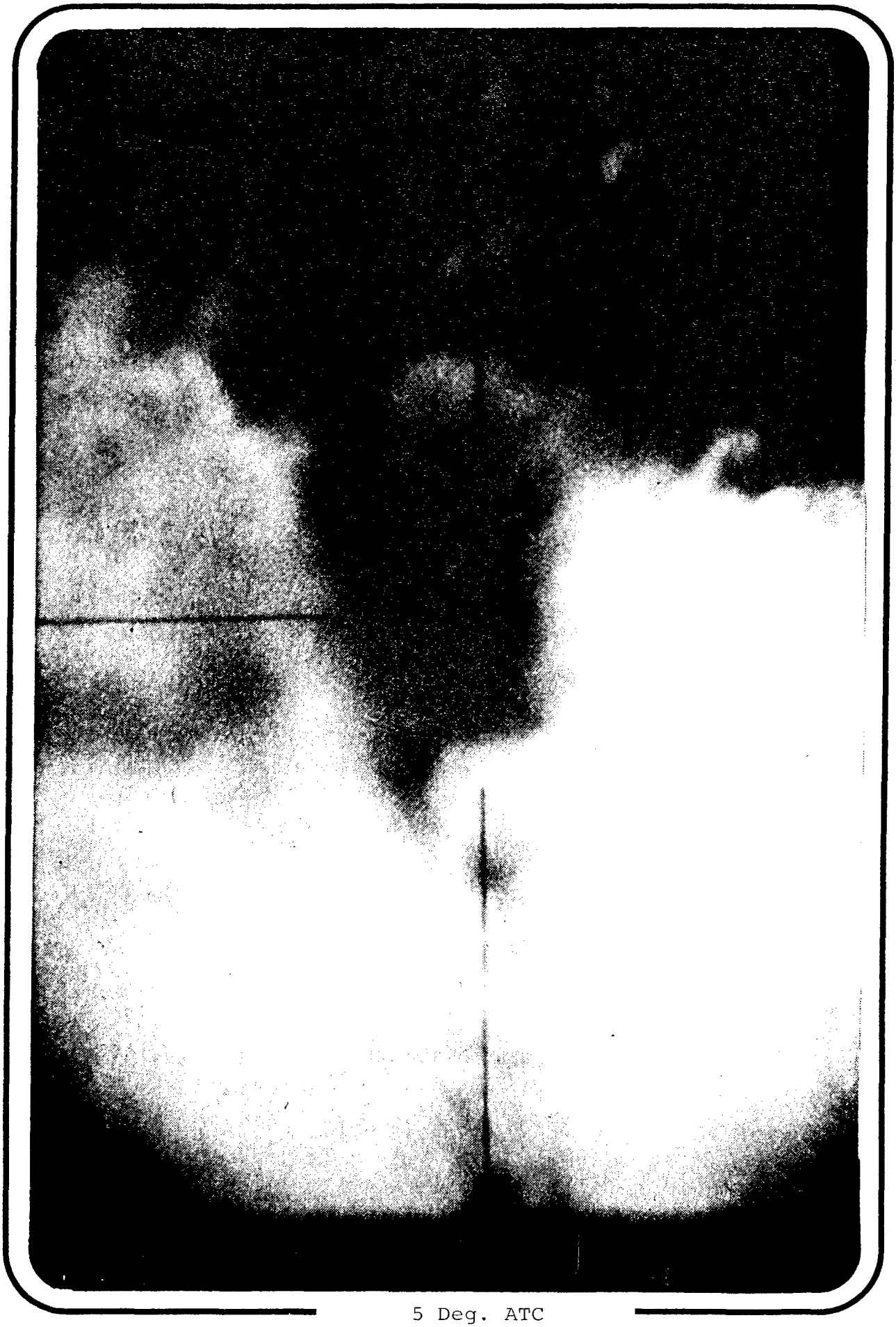
TDC
SERVOJET SR-1
12H23 C-40



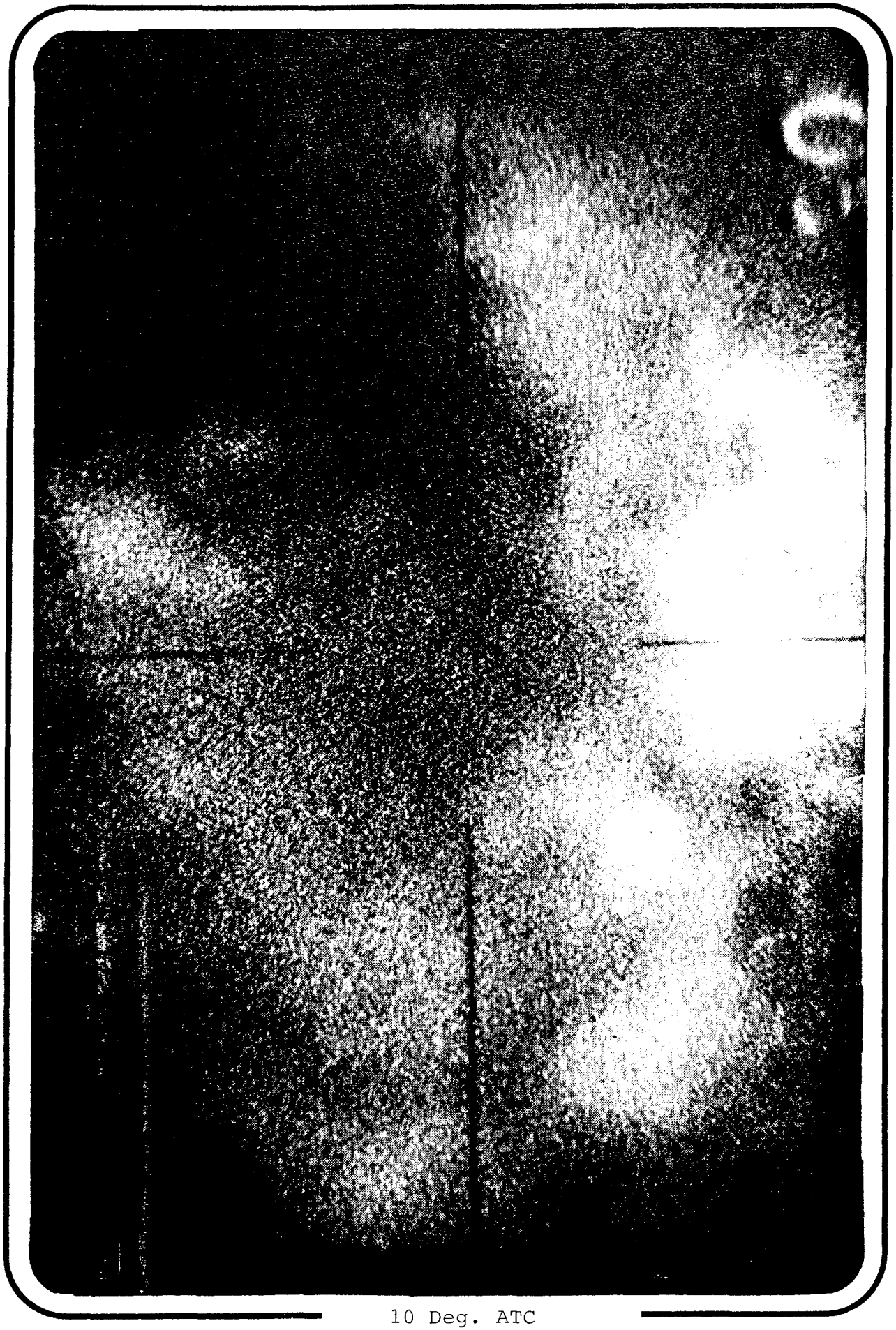
1 Deg. ATC
SERVOJET SR-1
12H23 C-41



2 Deg. ATC
SERVOJET SR-1
12H23 C-42



5 Deg. ATC
SERVOJET SR-1
12H23 C-43



10 Deg. ATC
SERVOJET SR-1
12H23 C-44

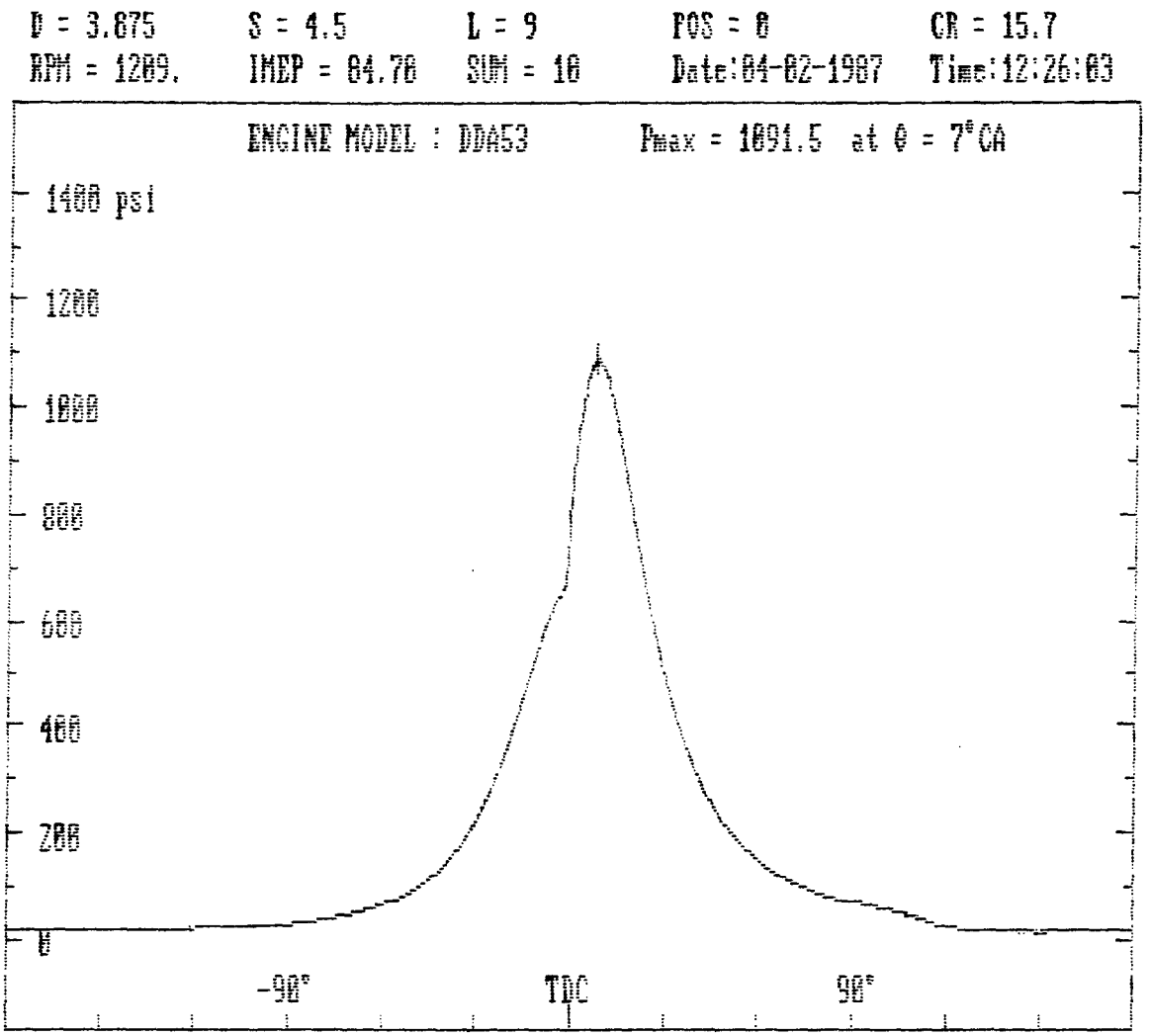
APPENDIX D

TEST DATA

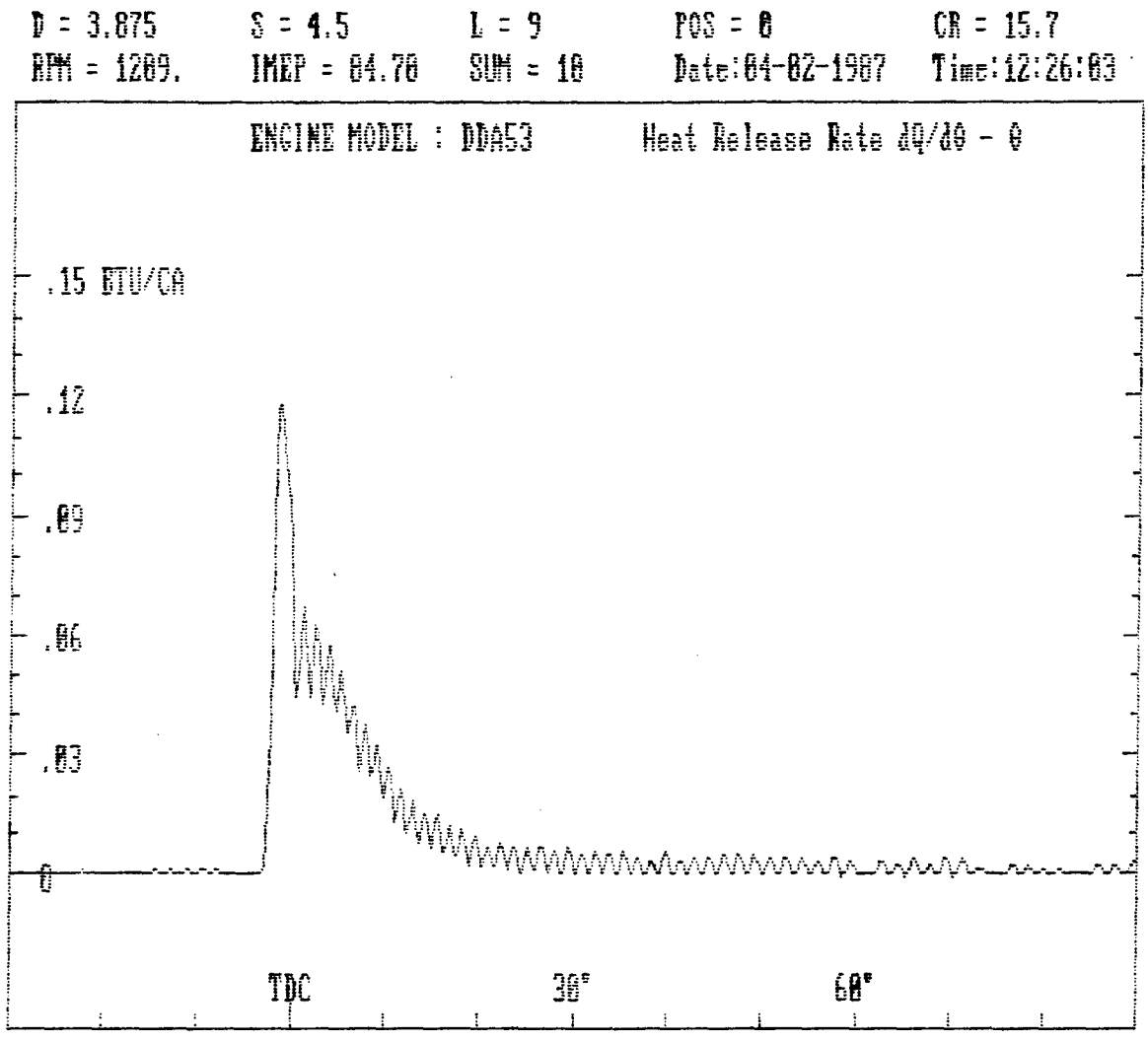
DDA Basline, TEST NUMBER 161-1

Test Line	0	1	10	6	7	8	9
Speed, RPM	1200	1200	1200	1200	1200	1200	1200
Torque, Lb-Ft	-21.8	.001	20	40	61	65	70
Delivery, mm^3/inj	0	16.9646	26.6374	44.3461	60.7155	64.287	70.2990
BMEP, PSI	-31.014	.001423	28.4528	56.9057	86.7811	92.4717	99.5849
Power, HP	-4.9810	.000228	4.56969	9.13938	13.9375	14.8515	15.9939
BSFC, Lb/HP-hr	0	9890.86	.776519	.646376	.580309	.576633	.585519
Smoke, BSU	0	.2	.3	2.9	3.4	3.4	4.2
Boost, psi	3	3	3	3	4	4	4
Exhaust Pressure, psi	1	1	1	1	2	2	2
NOx, ppm	0	202.605	452.735	715.371	832.932	827.930	825.429
Exhaust Temp. F	0	252	369	581	602	631	685
Timing, Deg.BTDC	0	9.36	10.08	10.8	12.96	12.96	13.32
Duration, degrees	0	4.32	7.2	7.92	11.52	12.24	12.6
Ignition Lag, deg.	0	9.36	8.64	7.92	7.92	7.92	7.56

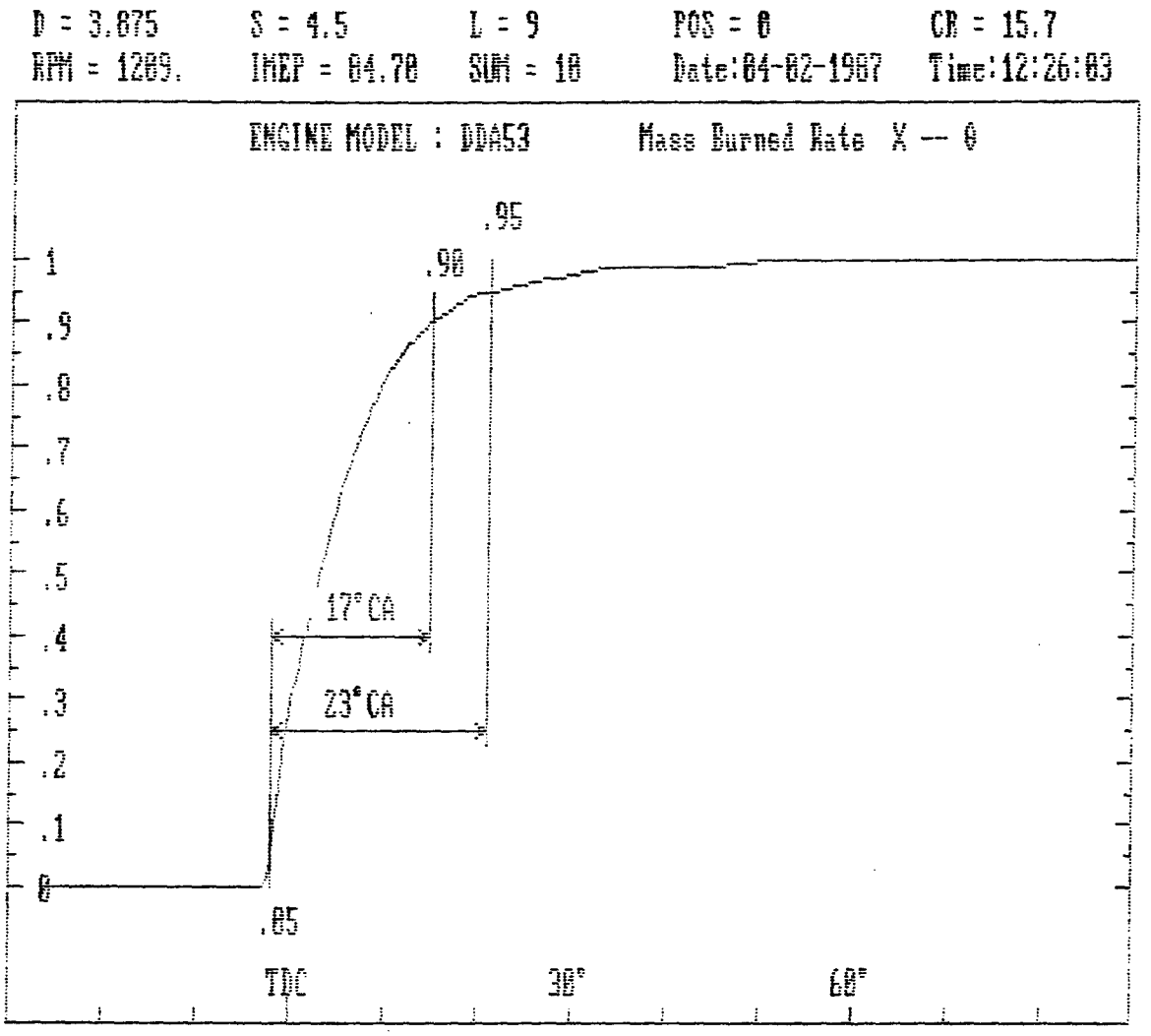
DDA -53
Baseline Test
Stock Injector
8 Hole Tip
161-1-6



DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-6



DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-6



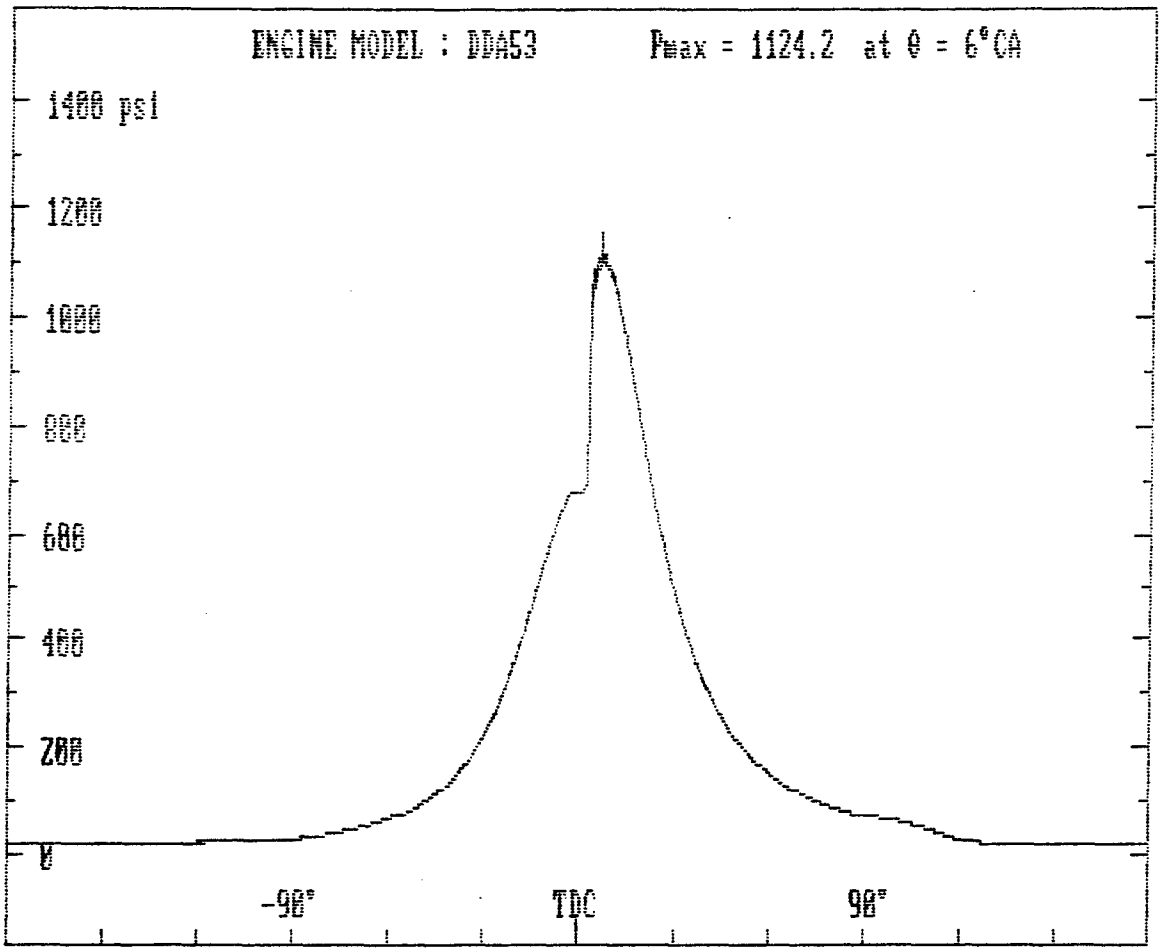
DDA - 53
Baseline Test
Stock Injector
8 Hole Tip
161-1-6

DDA-SR1 12 HOLE, TEST NUMBER 163-1

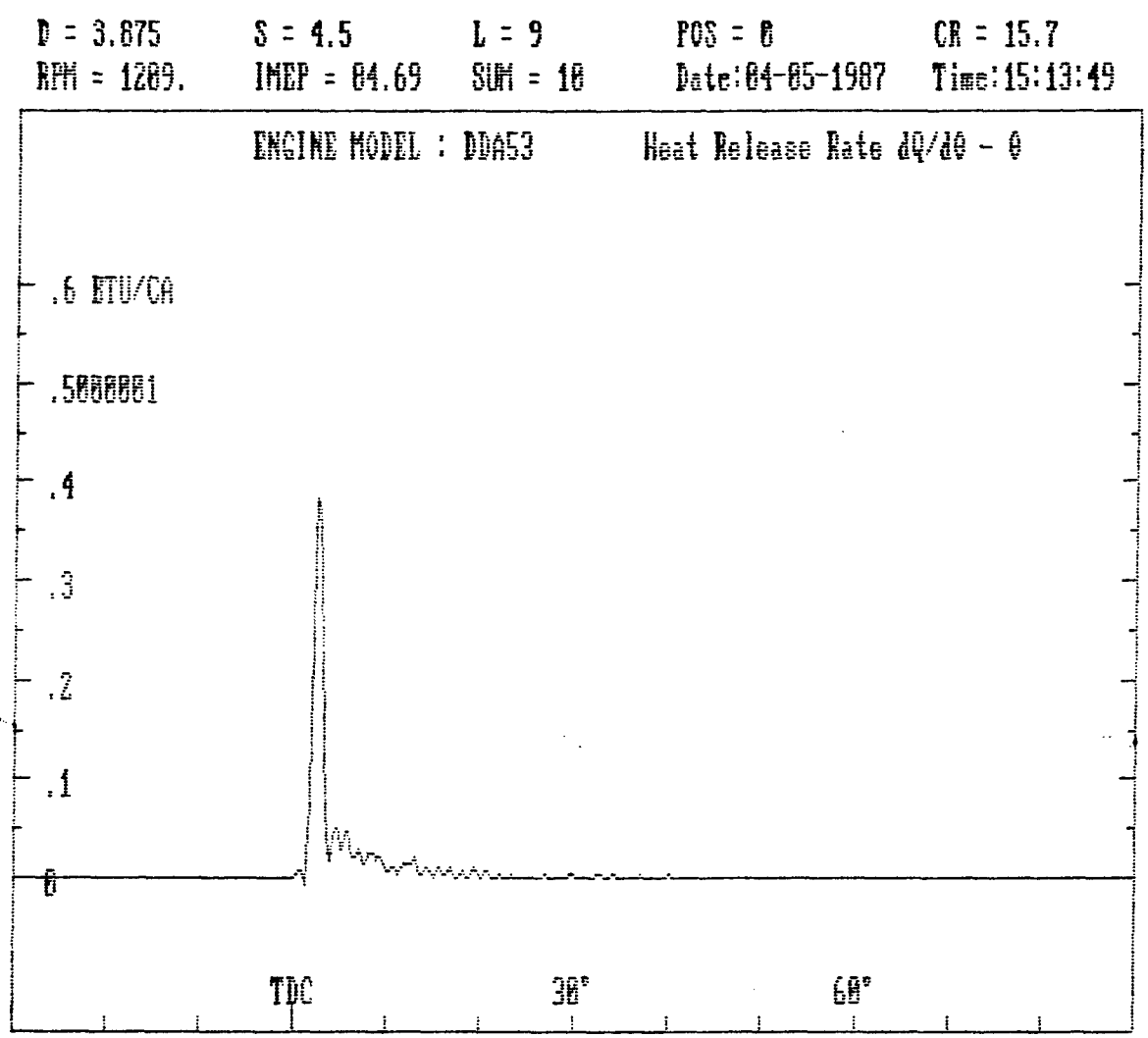
Test Line	0	1	2	4
Speed, RPM	1200	1200	1200	1200
Torque, Lb-Ft	-21.8	.1	20	40
Delivery, mm^3/inj	0	15.4170	27.1434	43.0366
BMEP, PSI	-31.014	.142264	28.4528	56.9057
Power, HP	-4.9810	.022848	4.56969	9.13938
BSFC, Lb/HP-hr	0	89.8854	.791269	.627289
Smoke, BSU	0	3.2	4.3	5.8
Boost, psi	3	3	3	3
Exhaust Pressure, psi	1	1	1	1
NOx, ppm	0	150.078	295.153	520.270
Exhaust Temp. F	0	279	413	536
Timing, Deg.BTDC	0	8.28	7.92	6.48
Duration, degrees	0	2.52	2.88	2.88
Ignition Lag, deg.	0	9.72	8.64	6.84

DDA - 53
Servojet Injector
12 Hole Tip
163-1-4

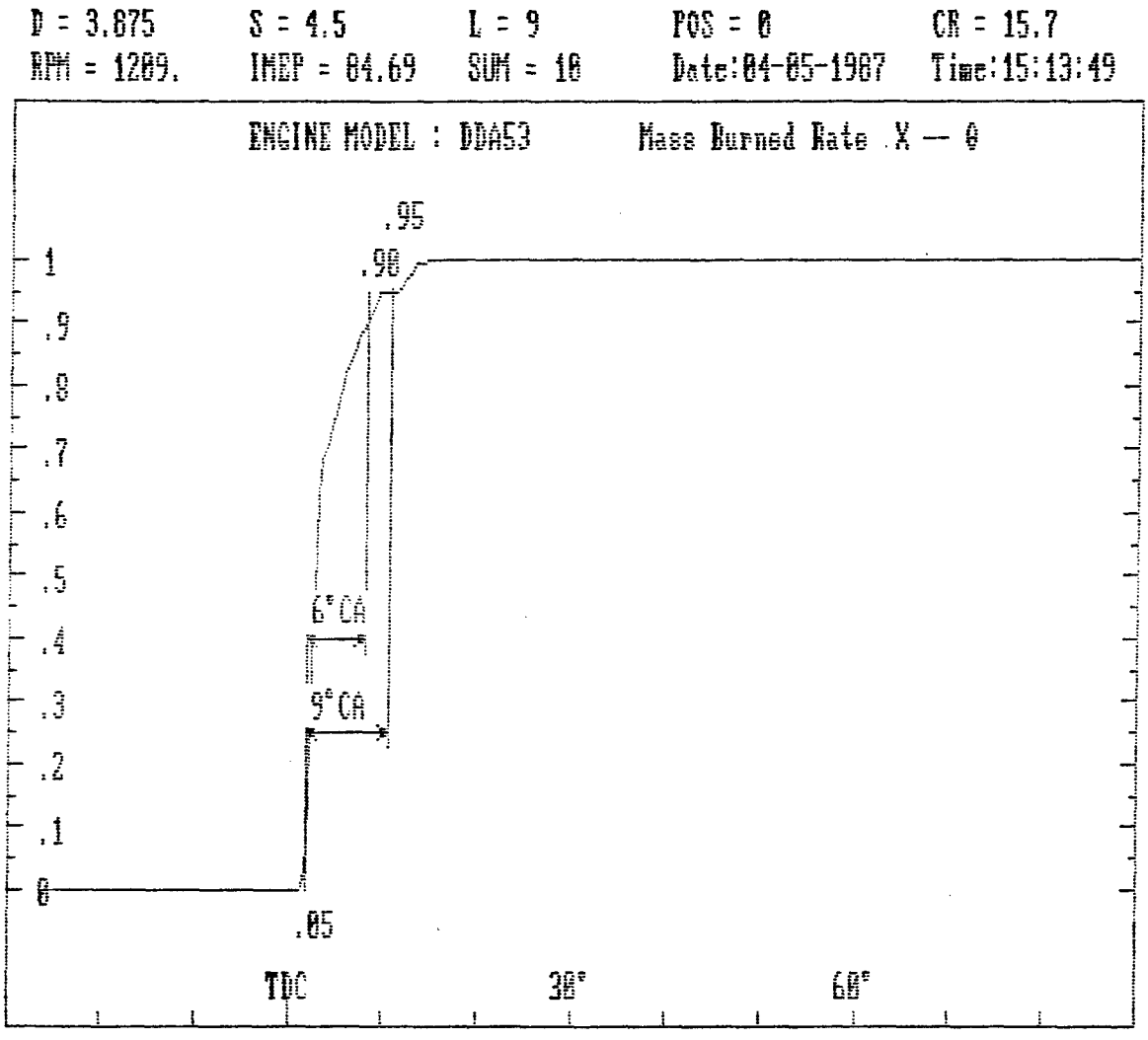
D = 3.875 S = 4.5 L = 9 POS = 0 CR = 15.7
RPM = 1269. IMEP = 64.69 SUM = 10 Date:04-05-1987 Time:15:13:49



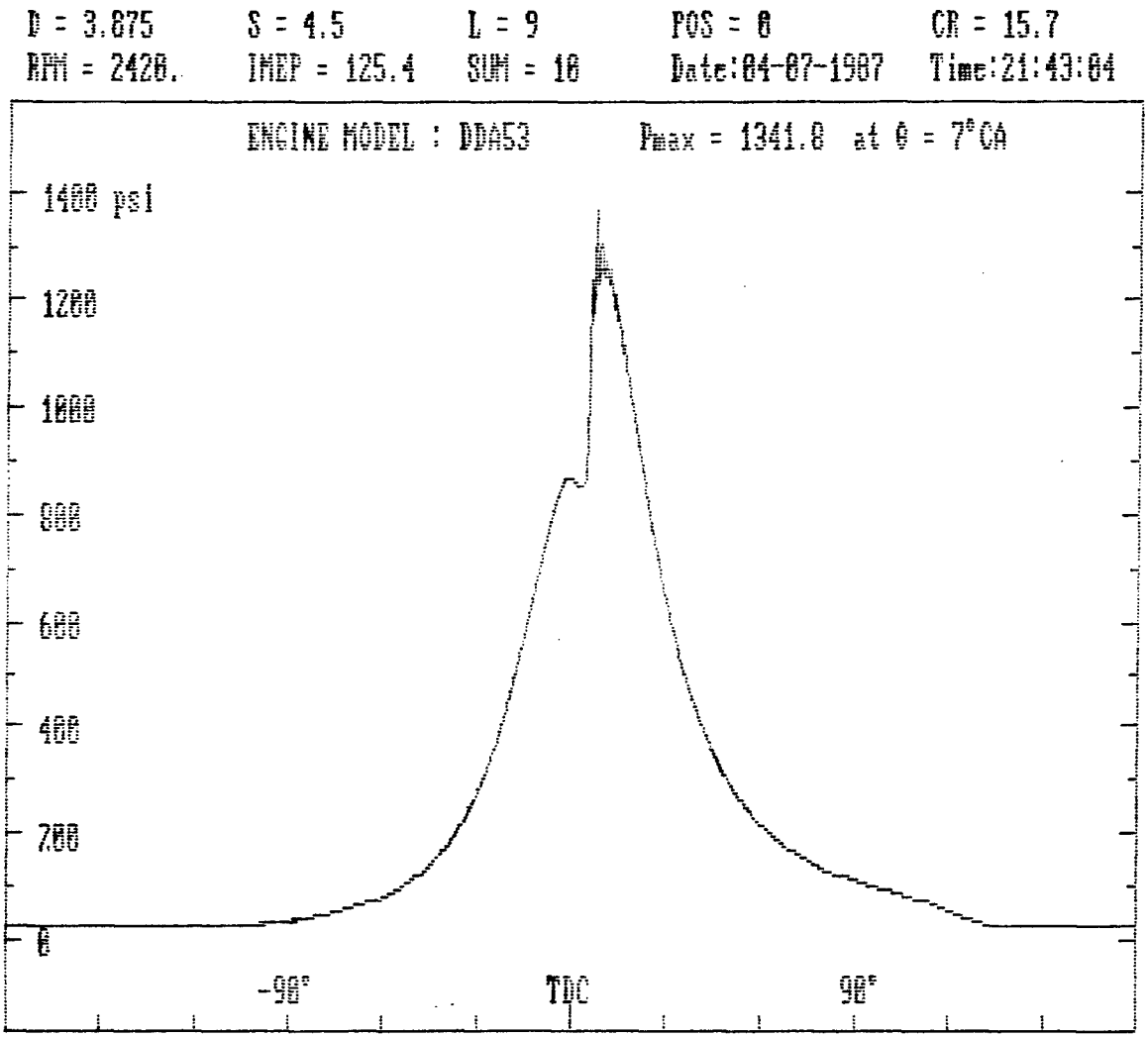
DDA - 53
Servojet Injector
12 Hole Tip
163-1-4



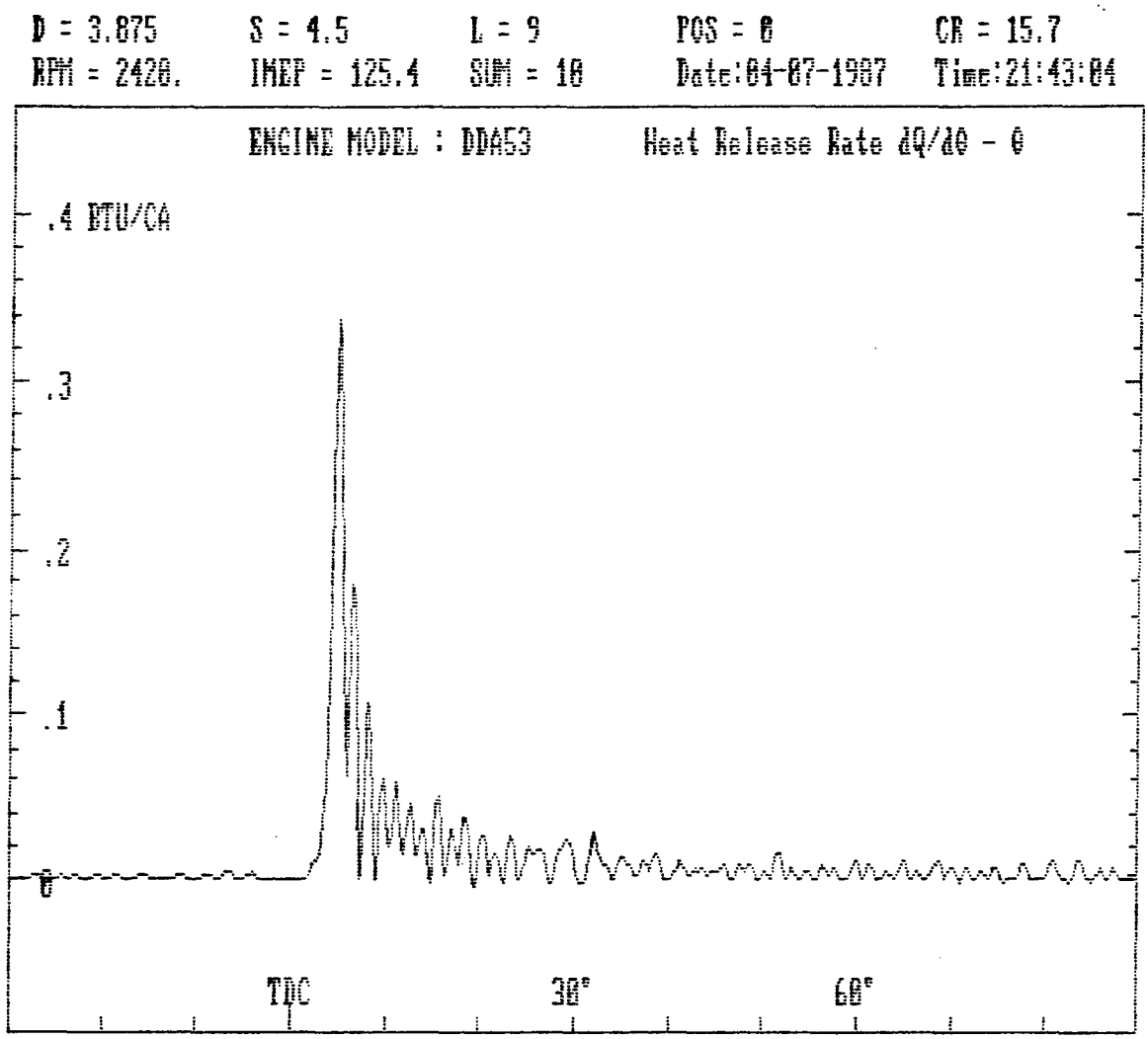
DDA - 53
Servojet Injector
12 Hole Tip
163-1-4



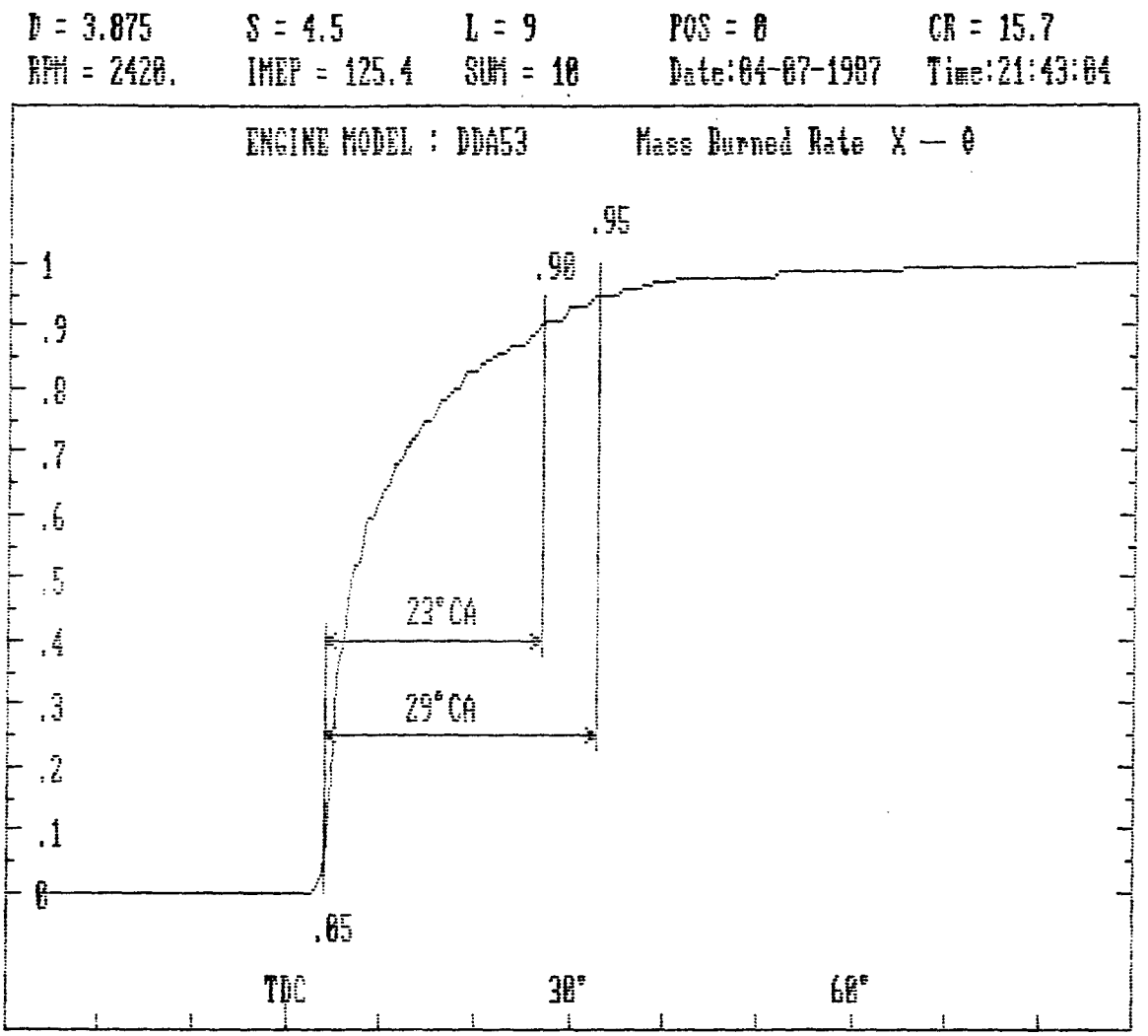
DDA - 53
Servojet Injector
12 Hole Tip
163-1-4



DDA - 53
Servojet Injector
8 Hole Tip
164-1-16



DDA - 53
Servojet Injector
8 Hole Tip
164-1-16



DDA - 53
Servojet Injector
8 Hole Tip
164-1-16

APPENDIX E

APPENDIX E

FINANCIAL STATEMENT
March 29, 1987 to June 21, 1987

CONTRACT NO. DAAE07-86-R069

DIRECT LABOR

Personnel Code No. or Function	Rate $/hour	# Hours	Total Direct Labor $	Overhead @ 120% $	G & A @ 15% $	Total $
144-73	25.00	33.0	825.00	990.00	123.75	1938.75
102-83	23.08	19.0	438.52	526.22	65.78	1030.52
160-82	18.27	6.0	109.62	131.54	16.44	257.60
163-79	18.27	356.0	6504.12	7804.94	975.62	15284.68
145-72	16.44	136.0	2235.84	2683.01	335.38	5254.23
Draftsman	15.00	12.25	183.75	220.50	27.56	431.81
Technician	12.94	14.5	187.63	225.16	28.14	440.93
Machinist	12.63	61.5	776.74	932.09	116.51	1825.34
	TOTAL	638.25	11261.22	13513.46	1689.18	26463.86

DIRECT MATERIAL	Cost $	Overhead @25% $	Total
	147.35	36.84	184.19
		TOTAL	$ 26648.05

APPENDIX E

PROJECT FINANCIAL SUMMARY
FINAL REPORT
August 4, 1986 to June 21, 1987

CONTRACT NO. DAAE07-86-R069

A) LABOR

Reporting Period	# Hours	Total Direct Labor	Overhead @ 120%	G & A @ 15%	Total
Aug 4 to Oct 19, 1986	393.5	9252.65	5286.17	1387.90	15926.72
Oct 20 to Mar 29, 1987	844.5	15246.72	15209.01	2286.99	32742.72
Mar 30 to June 21, 1987	638.25	11261.22	13513.46	1689.18	26463.86
TOTAL	1876.25	35760.59	34008.64	5364.07	75133.30

B) MATERIAL

Reporting Period	Direct Cost	Overhead @ 25%	Total
Aug 4 to Oct 19, 1986	172.66	43.16	215.82
Oct 20 to Mar 29, 1987	3156.82	789.20	3946.02
Mar 30 to June 21, 1987	147.35	36.84	184.19
TOTAL	3476.83	869.20	$ 4346.03

PROJECT TOTAL $ 79479.33

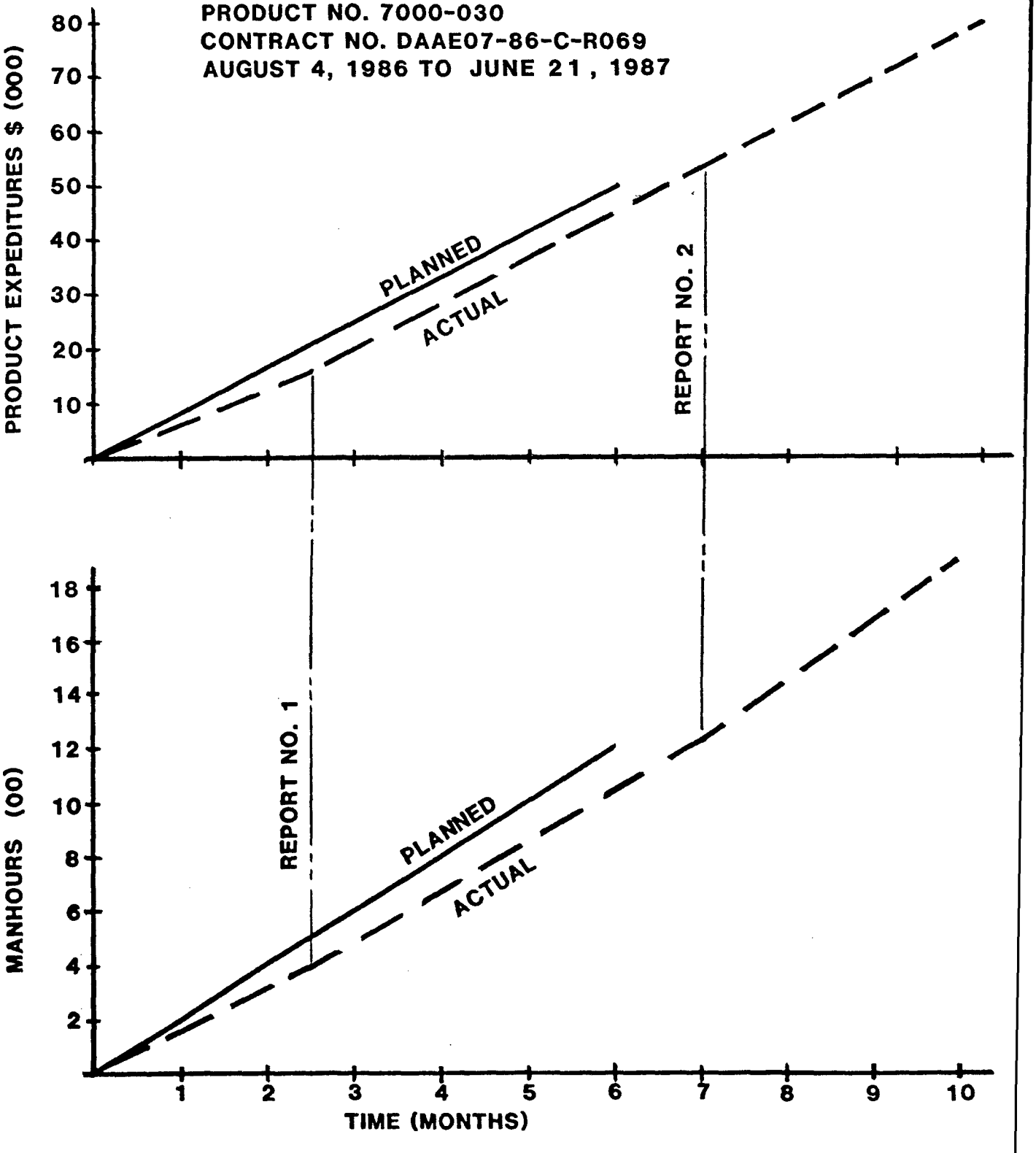
TOTAL BILLABLE $ 49908.00

APPENDIX F

APPENDIX F

EXPENDITURES & MANHOURS VS PLANNED

PRODUCT NO. 7000-030
CONTRACT NO. DAAE07-86-C-R069
AUGUST 4, 1986 TO JUNE 21, 1987



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